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NASA Project Apollo Working Paper No. 1101

AN EVALUATION OF THE THERMALLY RADIANT ENVIRONS OF A MAN ON THE LUNAR SURFACE

FACILITY FORM 602

~~X63-12347~~ (ACCESSION NUMBER)	N70-35808 (THRU)
94 (PAGES)	(CODE)
(NASA CR OR TMX OR AD NUMBER)	30 (CATEGORY)

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MANNED SPACECRAFT CENTER
Houston, Texas
November 22, 1963

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NASA PROJECT APOLLO WORKING PAPER NO. 1101

AN EVALUATION OF THE THERMALLY RADIANT ENVIRONS OF A MAN ON THE LUNAR SURFACE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

This paper presents the development of an analysis technique to evaluate various lunar environmental conditions and their effect on a pressure-suited man. The technique is established for the determination of the thermal, radiant, energy incident upon a man for three lunar surface conditions: plane, cliff, and crater. The utility of this analytical technique is evidenced by the detailed investigation presented for the lunar plane. The results of this investigation are presented in parametric form to allow the solution of specific problems over a wide range of variables. A typical problem would involve the quantitative determination of the effect of the lunar thermal environment on a man. Given the suit properties (solar absorptivity, emmisivity, and overall heat transfer coefficient) and position on the lunar surface, the heat leak (positive or negative) may be determined. A similar detailed investigation could be effected using the relationships developed within this paper for the cliff and crater.

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AN EVALUATION OF THE THERMALLY RADIANT ENVIRONS OF A MAN ON THE LUNAR SURFACE

1.0 OBJECTIVE

To gain an understanding of the thermal, radiant, energy incident upon a pressure-suited man on the illuminated portion of the moon's surface, an analytical study of various lunar environmental conditions was performed.

2.0 INTRODUCTION

The determination of the radiative heat incident upon a man on the surface of the moon is effected by the following heat transfer technique.

A differential area, dA_1, is positioned in the center of a sphere of radius ρ. Due to its temperature, T, dA_1 will radiate thermal energy at a rate of e according to the Stefan-Boltzmann equation, $e = \delta\epsilon T^4$ Btu/hr-ft^2. The radiation is assumed to be diffuse, obeying Lambert's Law, which states that the radiation intensity varies from the normal as the cosine of the angle. Thus, in figure 1, the intensity at point C, on dA_2, is $I_{normal} \cos \beta$, where I_{normal} is the intensity at point P, the intersection of the sphere and the normal to dA_1; and β is the angle made by the normal and the radius through C.

The relations developed in this report may also be applied to situations involving reflected energy as well as emitted energy as long as one presumes that the reflection is likewise diffuse. In such instances, the quantity e is simply replaced by the rate, per unit area, at which reflected radiation leaves the surface.

In order to utilize Lambert's Law in a heat transfer analysis, I_{normal} must be evaluated. It is evident from figure 1 that if dA_1 is emitting at the rate of e, then $e\,dA_1$ Btu/hr is the heat that will impinge on the hemisphere surrounding it. This must equal the sum of the products of the differential intensities on the hemispherical surface and their respective differential areas:

$$edA_1 = \int_{A_2} dI \, dA_2$$

$$edA_1 = \int_{A_2} dI_n \cos \beta \, dA_2$$

$$edA_1 = 4dI_n \int_{\beta = 0}^{\frac{\pi}{2}} \int_{\theta = 0}^{\frac{\pi}{2}} \cos \beta \sin \beta \, \rho^2 \, d\beta \, d\theta$$

$$edA_1 = \pi\rho^2 \, dI_n$$

$$dI_n = \frac{edA_1}{\pi\rho^2}, \qquad dI = edA_1 \frac{\cos \beta}{\pi\rho^2}$$

The intensity at the point C due to radiation from a surface of <u>finite</u> extent, A_1, may be obtained by integrating over the surface A_1:

$$I = \int_{A_1} dI = \int_{A_1} \frac{edA_1 \cos \beta}{\pi\rho^2}$$

$$I = \frac{e}{\pi} \int_{A_1} dA_1 \frac{\cos \beta}{\rho^2}, \text{ assuming } e \text{ constant}$$

For the purposes of this report, it is desirable to evaluate the radiant flux incident on an area of finite size, A, due to the emission from another finite area, A_1, as depicted in figure 1a. According to the above discussion, the energy falling on an element of A, dA, due to the emission of the finite area A_1 is shown on the following page.

$$dq = I(dA \cos \gamma) = dA \cos \gamma \frac{e}{\pi} \int_{A_1} \frac{\cos \beta \, dA_1}{\rho^2}$$

Where γ is the angle between the normal to dA and the line connecting dA to dA_1. The total energy falling on A is, per unit of receiving surface,

$$\frac{q}{A} = \frac{e}{A\pi} \int_A \int_{A_1} \frac{\cos \beta \cos \gamma \, dA_1 \, dA}{\rho^2} .$$

For most of the cases considered in this report the surface A_1 represents the lunar surface, and it is taken as infinite in extent. For such a set of conditions a simplification of the above expression can be made without incurring much error. If A (receiving surface) is small compared to A_1 (emitting surface) and if ρ is large, then as the integration is performed over the surface A, one may presume that ρ and β do not change very much. If this is true, then

$$\frac{q}{A} = \frac{e}{\pi} \frac{1}{A} \int_{A_1} \frac{\cos \beta}{\rho^2} \left[\int_A \cos \gamma \, dA \right] dA_1$$

The integral $\int_A \cos \gamma \, dA$ is the projected view of the surface A as seen from dA_1. Using A_p to denote this projection:

$$\frac{q}{A} = \frac{e}{\pi} \frac{1}{A} \int_{A_1} \frac{\cos \beta \, A_p}{\rho^2} dA_1$$

This simplification amounts to a "parallel ray" assumption wherein it is presumed that all rays from dA_1 to A are essentially parallel. The angle β and the distance ρ are measured with respect to some suitable midpoint of the projected area A_p. In general, ρ, β, and A_p are functions of the position of dA_1, and these functions must be found before performing the integration.

3.0 DISCUSSION

The evaluation of the thermal influence on a man of the varied lunar topography will be limited to three cases: radiation from a plain, a crater, and a cliff.

The plains of the moon will be the first considered. They are represented by an infinite plane, divided into differential areas. Each dA is assumed to radiate diffusely with an intensity of e Btu/hr-ft^2.

3.1 Multicylinder Man

The man may be represented by a combination of cylinders. The head, arms, and legs are circular cylinders, and the torso is an elliptic cylinder. The arrangement of these cylinders and the dimensions used are shown in figure 2. The analysis of the multi cylinder man starts with the head.

Figure 3 illustrates the geometry associated with the head. To use the final equation of section 2 to ascertain the radiant flux on the head due to the lunar plain, the projected area of the head, a vertical cylinder, as viewed from a point on the plain is needed. The line-of-sight is taken from dA_1 to the midpoint of the cylinder. Along this line-of-sight the projected area of the cylinder is a complex curvilinear trapezoid. However, in keeping with the "parallel ray" simplification made in section 2, this projected area is taken as a rectangle so that $A_p = HD \sin \phi$.

H = height

D = diameter

Thus, the total radiation received is

$$\frac{q}{A}_{head} = \frac{4HDe/\pi}{HD\pi} \int_{r=0}^{\infty} \int_{\theta=0}^{\frac{\pi}{2}} \frac{\cos \phi \sin \phi \, r dr \, d\theta}{\rho^2} .$$

ϕ = angle between the normal to dA and line-of-sight to the cylinder

ρ = distance from dA to the man

In the above integral $\sin \phi$, $\cos \phi$, and ρ may be expressed in terms of r and the distance from the plain to the midpoint of the cylinder, C. The resulting integration yields $\frac{q}{A} = 0.5e$. The integration process reveals that if the plane considered is infinite, the distance C may be any positive finite value other than zero without affecting the results. When the plane is finite, and C = 5.5 feet, a similar integration shows that $\frac{q}{A}$ varies in the following manner:

r (feet)	100	500	1,000	10,000
$\frac{q}{A}$ (Btu/hr-ft^2)	0.465 e	0.493 e	0.496 e	0.4999 e

The arm is represented by a circular cylinder whose axis is parallel to the infinite plane (fig. 4). Any shielding effect by the body is neglected. Again, the projected area is taken to be a rectangle.

For either arm,

$$\frac{q}{A} = \frac{4HDe/\pi}{\pi DH} \int_{\theta=0}^{\frac{\pi}{2}} \int_{r=0}^{\infty} \frac{\cos \phi \cos \phi \, r dr \, d\theta}{\rho^2}$$

$$\frac{q}{A} = 0.5e$$

The torso, an elliptic cylinder, is next considered. Figure 5 illustrates the geometry of the situation. The heat flux, per unit area, to the torso is once again found by taking the projected area to be a rectangle so that $A_p = HC_p \sin \phi$. In this case, C_p represents the width of the ellipse as viewed from dA_1. Thus C_p is a function of the angle θ, for the "parallel ray" case, and appendix A shows that

$$C_p = 2a \sqrt{1 - \left(\frac{a^2 - b^2}{a^2}\right) \cos^2 \theta}$$

where a and b represent the semimajor and minor diameters of the ellipse, respectively.

Thus, for the torso

$$\frac{q}{A} = \frac{4He/\pi}{A_{torso}} \int_{\theta=0}^{\frac{\pi}{2}} \int_{r=0}^{\infty} \frac{\cos \phi \sin \phi \, C_p \, r \, dr \, d\theta}{\rho^2}$$

For an elliptical cylinder

$$A_{torso} = 4Ha \int_0^{\frac{\pi}{2}} \sqrt{1 - \left(\frac{a^2 - b^2}{a^2}\right) \sin \theta} \, d\theta$$

Thus, appropriate integration will yield

$$\frac{q}{A} = 0.5e.$$

The legs are shown in figure 6. The basic problem here is to account for the shading of one leg by the other. Considering, for instance, the cylinder X in figure 6, the radiation it receives from quadrants 1 and 2 of the lunar plain should be exactly one-half that received by a vertical cylinder from the entire lunar plain, as already found in the case of the head. Thus,

$$\left(\frac{q}{A}\right)_{1,2} = 0.25e$$

The radiation from quadrants 3 and 4 to cylinder X is shaded by cylinder Y. Appendix A shows that the projected length of the circumference of cylinder X as viewed from quadrants 3 and 4 is D cos θ. Thus, A_p = DH sin ϕ cos θ, and

$$\left(\frac{q}{A}\right)_{3,4} = \frac{2\ DH\ e/\pi}{\pi DH} \int_{r=0}^{\infty} \int_{\theta=0}^{\frac{\pi}{2}} \frac{\cos \phi \sin \phi \cos \theta \, r \, dr \, d\theta}{\rho^2}$$

$$= \frac{e}{2\pi} = 0.159\ e.$$

Thus, the total heat flux received by one leg is

$$\frac{q}{A} = (0.25 + 0.159)e = 0.409\ e.$$

To ascertain the heat flux on the entire multicylinder body, per unit total surface area, the $\frac{q}{A}$ values obtained above are each multiplied by the percentage of the total surface contributed by each member and the results summed. For the proportions shown in figure 2, this results in

$$\frac{q}{A} = 0.463\ e .$$

3.2 Hemisphere-Cylinder Man

A serious disadvantage in ascertaining radiation to the multicylinder man is the difficulty in determining the projected areas of its various members. A simple geometric configuration having a $\frac{q}{A}$ that approximates that of the multicylinder man was found to be a circular cylinder body with a hemisphere head (fig. 7).

The $\frac{q}{A}$ for the head is (fig. 8)*:

$$\frac{q}{A} = \frac{4\ e/\pi}{2\pi a^2} \int_{\theta=0}^{\frac{\pi}{2}} \int_{r=0}^{\infty} \frac{\cos \phi}{\rho^2} \frac{\pi a^2}{2} (1 - \cos \phi)\ r\ dr\ d\theta$$

$$\frac{q}{A} = 0.25\ e$$

The equation used to determine the radiation incident on the head of the multicylinder man is now used for the body of the hemisphere-cylinder man.

$$\frac{q}{A} = \frac{4\ DH\ e/\pi}{\pi DH} \int_{r=0}^{\infty} \int_{\theta=0}^{\frac{\pi}{2}} \frac{\cos \phi \sin \phi\ r\ dr\ d\theta}{\rho^2}$$

$$\frac{q}{A} = 0.5\ e$$

Taking the height of the cylinder to be 5 feet, and its diameter to be 1.52 feet, the cylinder is 86.5 percent and the hemisphere 13.5 percent of the total surface area. Multiplying these percentages by

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*For the manner in which the projected area of the head was determined, see appendix B.

their respective value of $\frac{q}{A}$ and combining the results, yields an effective $\frac{q}{A}$ of 0.466e for the entire body. This value of $\frac{q}{A}$ is quite close to that of 0.463e obtained for the multicylinder man. Therefore, the hemisphere-cylinder man will be utilized for subsequent analyses.

3.3 Radiation Absorbed by Man

Thus far, the effect of solar radiation upon the man and upon the lunar surface has not been considered. The moon is a planetoid; its only significant source of heat is the sun. Therefore, the lunar temperature at any point is a function of the incident solar radiation. Due to its relatively slow rotational speed, the temperature attained at any point on the moon's surface is approximately the equilibrium temperature. To determine a temperature profile for the lunar equator, the solar flux distribution must be known. (The lunar equator will be considered as the locus of subsolar points. The equator is actually 1°32' from the ecliptic.)

An energy balance between the absorbed and emitted energy on the moon's surface gives $e = G_n\ (1-a)$ in which G_n represents the solar flux normal to the surface and (a) represents the moon's albedo. If G_s represents the solar constant at the moon (that is, the normal flux at the subsolar point) then a factor, F_s, may be defined

$$F_s = G_n/G_s.$$

By simple geometrical reasoning one concludes that $F_s = \sin\theta$, where θ is the longitude measured from the dawn-point. However, at $\theta = 0°$ the above relation yields $F_s = G_n = e = 0$. This fact is not in agreement with lunar observations. Lunar temperature curves (ref. 1) yield $e_0 = 16$ Btu/hr-ft^2 and $e_{90} = 410$ Btu/hr-ft^2. For the purpose of this paper, it is presumed that $F_s = \sin\theta$ holds near the subsolar point and that this variation be allowed to blend into a tangent straight line such that

$$F_s = e_0/e_{90} = \frac{16}{410} = 0.039$$

at $\theta = 0$. The requirement that $e_{90} = 410$ Btu/hr-ft^2 is satisfied

by taking the albedo, a = 0.07. These facts are illustrated in figure 9 and result in:

$$e = G_s F_s (1-a)$$

$$G_s = 440 \text{ Btu/hr-ft}^2$$

$$a = 0.07$$

$$F_s = \sin\theta; \quad 28.26° \leq \theta \leq 90°$$

$$F_s = 0.039 + 0.8808\,\theta; \quad 0° \leq \theta \leq 28.26°$$

The constants in the above relations were obtained by matching, analytically, the slopes of the sine curve and the straight line. Using $e = \epsilon_m \sigma T^4$, the temperature profile, as a function of position along the equator, may be obtained when the lunar surface emissivity $\epsilon_m = 1.0$ is used. These results are given in figure 10.

The lunar flux profile, as determined from figure 9, makes possible the calculation of the total Btu/hr absorbed by a hemisphere-cylinder man as his position varies from the subsolar point to the dawn point on the flat lunar plain. The total radiant heat absorbed by the man from direct solar radiation, moon radiation, and the moon's albedo at various positions between these two points is shown in figures 11, 12, 13, and 14. The emissivity (ϵ)* and solar absorptivity (α_s) of the surface of the man were assigned values of 0.05, 0.15, 0.3, 0.5, 0.7, 0.85, 0.95; and 0.1, 0.15, 0.2, and 0.3, respectively. A figure was drawn for each absorptivity; and ϵ, as the parameter, was allowed to vary over the range 0.05 to 0.95.

These curves were calculated from the following relation which is derived in appendix C.

$$Q_{abs}/A_t = G_s \left\{ \alpha_s F_m + \left[\epsilon\ (1 - a) + \alpha_s a \right] F\ F_s \right\}$$

In the above equation G_s, α_s, ϵ, a, and F_s have already been defined. Q_{abs} denotes the total radiant heat absorbed by the man and A_t the total surface area. The factor F_m represents the ratio of the projected surface area of the man, normal to the sun's rays, to the total

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*The "mean value" of the emissivity (or absorptivity) function, $f(\lambda)$ (from $\lambda = 3\mu$ to ∞) = ϵ (epsilon).

surface, A_t, and for the hemisphere-cylinder is given by

$$F_m = \frac{\frac{1}{\pi}\cos\theta + \frac{1}{8}\frac{D}{H}(1 + \sin\theta)}{1 + \frac{1}{2}\frac{D}{H}}.$$

The factor F represents the fraction of the radiation leaving the moon's surface which strikes the man, per unit of total surface. Thus, F is simply the coefficient of e in the relations derived in sections 3.1 and 3.2. For the case of the hemisphere-cylinder representation, F has already been found to be $F = 0.466$. For the purposes of calculating figures 11 through 14, the function F_s was represented by the equations shown in figure 9. The dimensions used were

$$H = 5.0 \text{ ft}, \quad D = 1.52 \text{ ft}$$

The above equation for (Q_{abs}/A_t) may be used for other assumed configurations of the man, but appropriate relations for F and F_m would then have to be found.

The curves of figures 11 through 14 illustrate that for an $\epsilon = 0.05$, the man receives more heat at the dawn point, $\theta = 0°$ than at the subsolar point, $\theta = 90°$. This is due to the relatively small emphasis placed on lunar heat by the ϵ value of 0.05. For other ϵ's considered, however, more heat is received at subsolar than at the dawn point.

All curves indicate a value of θ for which the heat absorbed by the man was greatest. This angle for maximum heat absorption may be determined analytically from the above equation for (Q_{abs}/A_t) when the appropriate relations for F, F_m, and F_s are used. These relations are derived in appendix C, and the results are applied to the case of the hemisphere-cylinder man considered in this report. The results show that this angle of maximum heat absorption, $\theta_{Q_{max}}$, is dependent (for a given geometry) only on the ratio ϵ/α_s. This relation is plotted in figure 15, and in a more directly usable form, in figure 16. It is seen that as ϵ/α_s decreases, the point of maximum heat absorption moves from near subsolar points toward the dawn point.

3.4 Heat Conducted Through Surface Insulation

The quantity of heat absorbed by the outer skin and conducted through the insulation of the hemisphere-cylinder man is dependent upon the magnitude of absorbed radiation, the emissivity (ϵ) of the outer skin, and the thermal conductivity (k) and thickness (ΔX) of the insulating material (see figs. 17 – 27A).

A heat balance for the insulating material on the man gives

$$Q_{abs}/A_t = Q_r/A_t + Q_c/A_t$$

where Q_r and Q_c represent the heat radiated by the surface and the heat conducted into the interior, respectively. Thus,

$$Q_r/A_t = \epsilon \sigma T^4$$

$$Q_c/A_t = \frac{k}{\Delta X} (T - T_i)$$

where T_i = inner skin temperature of the insulation.

One has then

$$Q_{abs}/A_t = \epsilon \sigma T^4 + Q_c/A_t$$

$$Q_c/A_t = \frac{k}{\Delta X} (T - T_i)$$

For a given inner skin temperature, the above two equations can be solved together to eliminate the surface temperature, T, and yield a relation between the absorbed heat, the conducted heat, the surface emissivity, and the suit properties. Figures 17 through 27A were constructed in this manner.

In these figures, the inner skin temperature was taken as 75° F. The curves were plotted for a range of values of $\frac{k}{\Delta X}$ = U of 0.001 to 6 and a range of ϵ of 0.05 to 0.95. (U = Btu/hr-ft^2 - °F) The curves show that for most ϵ and U there are values of the absorbed heat for which there is a negative conducted heat (that is, heat flow from the inner to outer skin). It is also apparent that for each ϵ there is a value of the absorbed heat for which there is no heat conducted through the insulation, that is, $T = T_i$. This "zero heat leak" condition occurs when $Q_{abs}/A_t = \epsilon \sigma T_i^4$.

In figure 28, this condition is plotted for $T_i = 75°$ F.

To demonstrate the utilization of figures 17 to 27A in conjunction with figures 11 to 14, an example will be given. The heat conducted through the insulation of a space-suited man is sought. His suit properties are $\alpha_s = 0.3$, $\epsilon = 0.7$, and $U = 6$; he is standing at a position 30° from the dawn point. From figure 14, it is seen that he absorbs 107 Btu/hr-ft^2. Then, using figure 23A, it is seen that 7.5 Btu/hr-ft^2 is conducted through the suit.

3.5 Presence of Craters and Cliffs

The lunar surface is characterized by craters and mountain ranges, both of which contribute to the radiant heat received by the man. The second surface feature to be considered is the crater.

For mathematical analyzation purposes, a crater may be simulated by a right circular cylinder. The analysis of thermal radiation contributed by the crater to a hemisphere-cylinder man in its center is divided into parts, the body and the head.

The same methods as outlined in sections 1 and 2 were used in this instance, that is, the receiving area is small compared with the emitting area and "parallel ray" projections are used. Thus, without detailed discussion, one obtains the following results.

The incident radiation on the body is: (fig. 29)

$$\frac{q}{A} = \frac{4\ DH\ e/\pi}{\pi DH} \int_{\omega=0}^{\frac{\pi}{2}} \int_{\theta=0}^{\frac{\pi}{2}} \frac{\cos\ \omega\ \cos\ \omega\ \rho d\omega\ X\ d\theta}{\rho^2\ \cos\ \omega}$$

$$\frac{q}{A} = 0.5\ e.$$

The radiant heat received by the head is: (fig. 30)

$$\frac{q}{A} = \frac{4\ e/\pi}{2\pi a^2} \int_{\omega=0}^{\frac{\pi}{2}} \int_{\theta=0}^{\frac{\pi}{2}} \frac{\cos\ \omega}{\rho^2} \frac{\pi a^2}{2} (1 + \sin\ \omega)\ X\ d\theta\ \rho\ \frac{d\omega}{\cos\ \omega}$$

$$\frac{q}{A} = \frac{3}{4}\ e = 0.75\ e$$

These results were obtained by allowing the crater walls to be of infinite height. When this condition exists, the distance, D, from the sides of the crater to the man, is of no importance. For finite heights of the crater walls, however, $\frac{q}{A}$ is proportionately reduced. Figure 31 shows the manner in which $\frac{q}{A}$ for a hemisphere-cylinder man varies with the ratio of the height of the walls to the man's distance from the walls $(\frac{D}{H})$.

It is to be noted that preceding analyses have shown that a cylinder placed in a crater, whose diameter and height are infinite, receives a $\frac{q}{A}$ of 0.5e each from both the crater walls and the lunar plain, giving a total $\frac{q}{A}$ of e. Similarly, a hemisphere receives a $\frac{q}{A}$ of 0.25e + 0.75e = e. It may also be said that for sufficiently large finite crater dimensions, the $\frac{q}{A}$ of the hemisphere-cylinder man is essentially e.

The third topographical feature of the lunar surface considered is a sheer cliff. To analyze its thermal effect on a hemisphere-cylinder man, the cliff is simulated by an infinite plane perpendicular to the lunar plain. A cylinder at a distance, D, from the cliff will receive a $\frac{q}{A}$ of: (fig. 32)

$$\frac{q}{A} = \frac{2\ DH\ e/\pi}{\pi DH} \int_{y=0}^{\infty} \int_{z=0}^{\infty} \frac{\cos \phi \cos \omega \, dz \, dy}{\rho^2}$$

$$\frac{q}{A} = 0.25\ e$$

For the radiation from a cliff to the hemisphere one has: (fig. 33)

$$\frac{q}{A} = e/\pi \int_{\phi=0}^{\frac{\pi}{2}} \int_{\theta=0}^{\pi} \frac{\cos \phi \,(1 + \sin \phi)(r\, d\theta) \left(\frac{\rho\, d\phi}{\cos \phi}\right)}{\rho^2}$$

$$= e/2 = 0.5\ e$$

The above integral results when one assumes the cliff to be of infinite extent so that the height of the hemisphere above the plane can be neglected.

The results of this section may be incorporated in an analysis similar to that in paragraph 3.4, section 3, to evaluate the total heat absorbed by a man in a crater or near a cliff. Appropriate values of the parameters F, F_m, and F_s would have to be used for the particular geometrical orientation of the lunar surface being considered.

4.0 CONCLUDING REMARKS

The value of this paper lies in its ability to provide a quantitative evaluation of the effect of the lunar thermal environment on a pressure-suited man. Since the results of the investigations are presented in parametric form, solutions of specific problems over a wide range of variables are easily effected. It is believed that the assumptions and guidelines used in the performance of this study are valid and have yielded a meaningful determination.

Interpretations and extrapolations of the data presented within this report are possible, without loss of confidence in the results, if the basic study premises are used as restraints. Several of the more important postulations are: geometry simplifications for the man and the lunar surface were used, all radiation and reflections are diffuse, the lunar terrain-man surface of contact is adiabatic, the suit radiant characteristics and overall heat transfer coefficient are unchanging over the man-model surface, and the effects of directly transmitted radiation (such as through a visor) are not considered.

5.0 REFERENCES

1. Kopal, Zdenek: "Physics and Astronomy of the Moon," Academic Press, New York, 1962, p. 411. (From the measurements of Dr. William N. Sinton, of Lowell Observatory, Flagstaff, Arizona.)

6.0 FIGURES

Figure 1.- Differential area radiating to a sphere

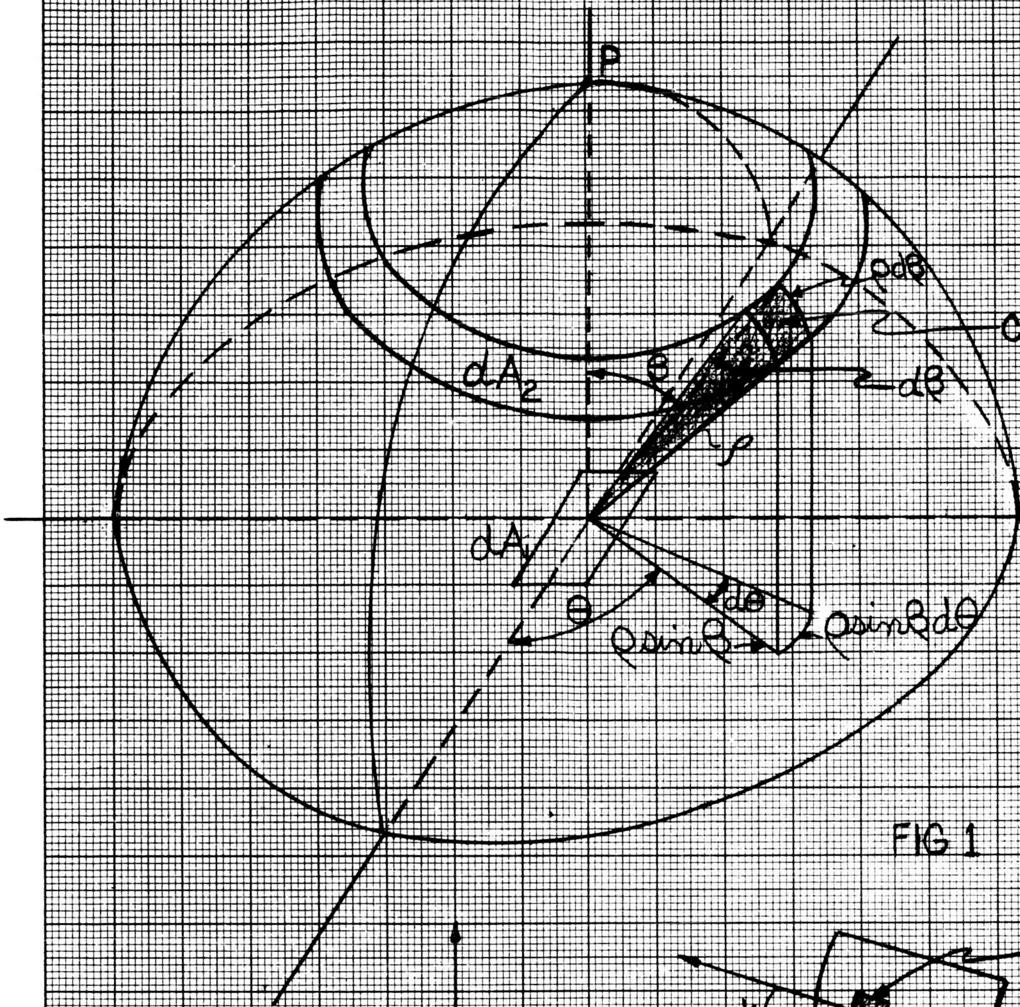


FIG 1

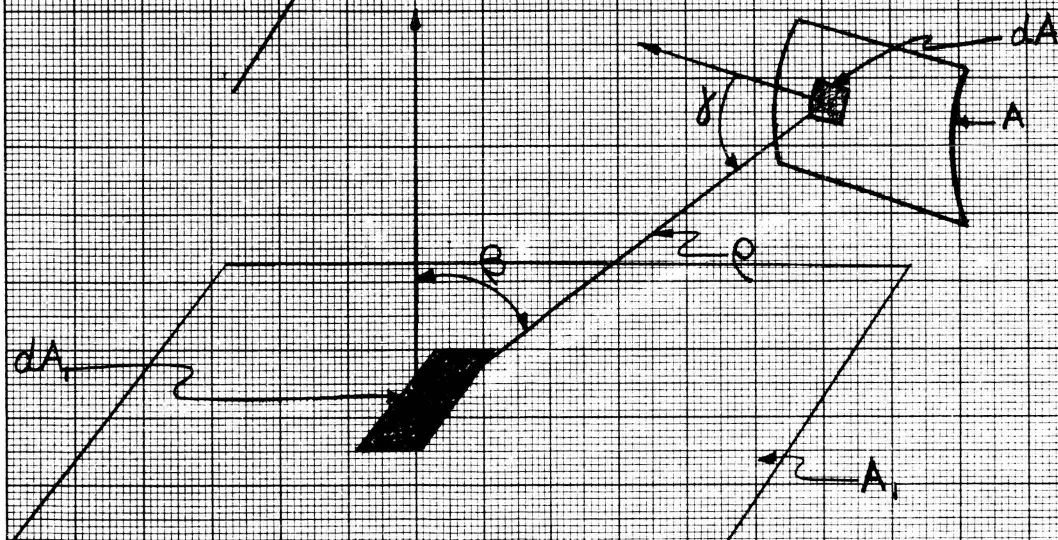


FIG 1a.

Figure 1A.- Differential area radiating to a finite area

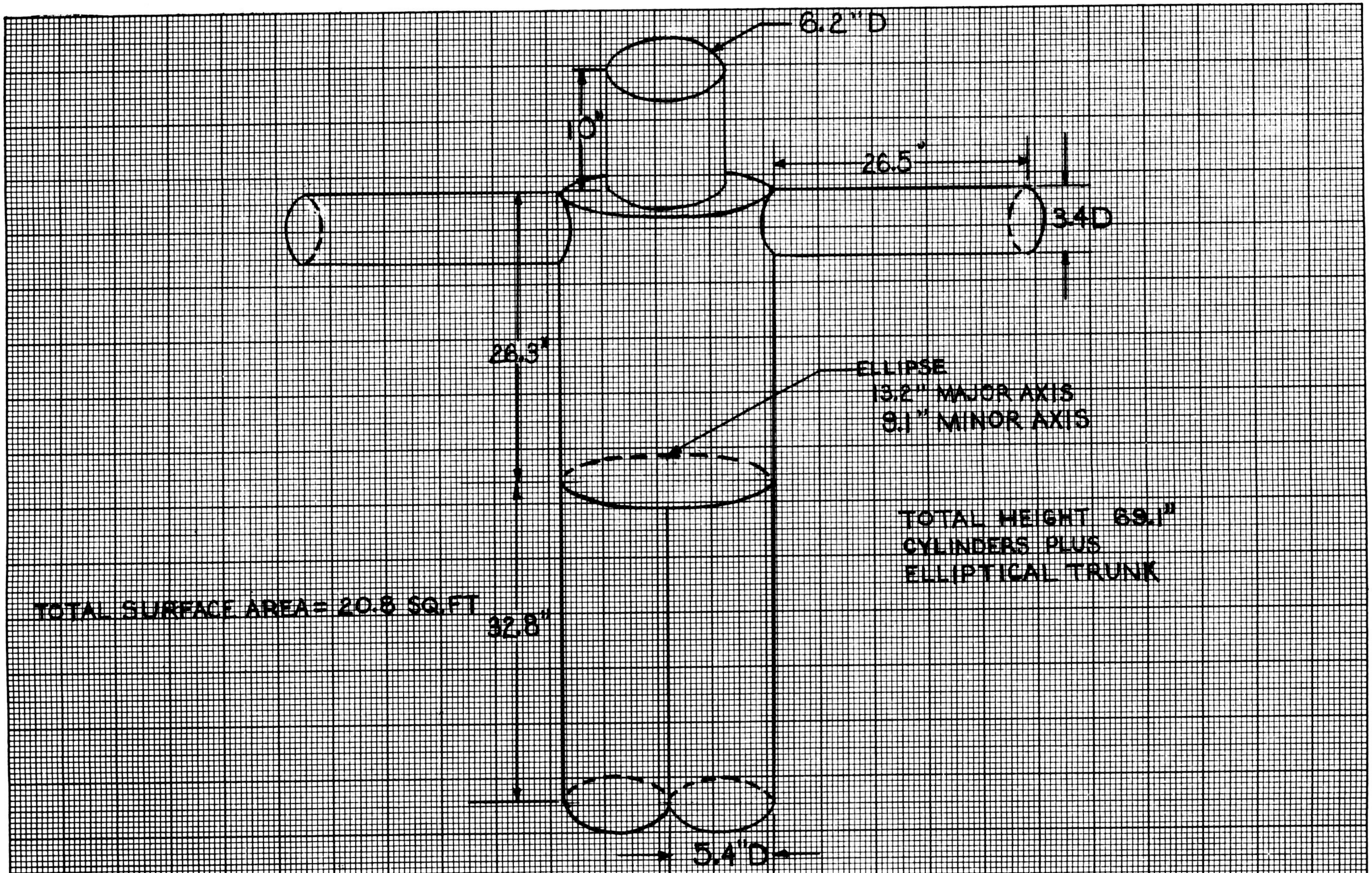


Figure 2.- Multicylinder man

RADIATION FROM LUNAR
PLAIN TO HEAD

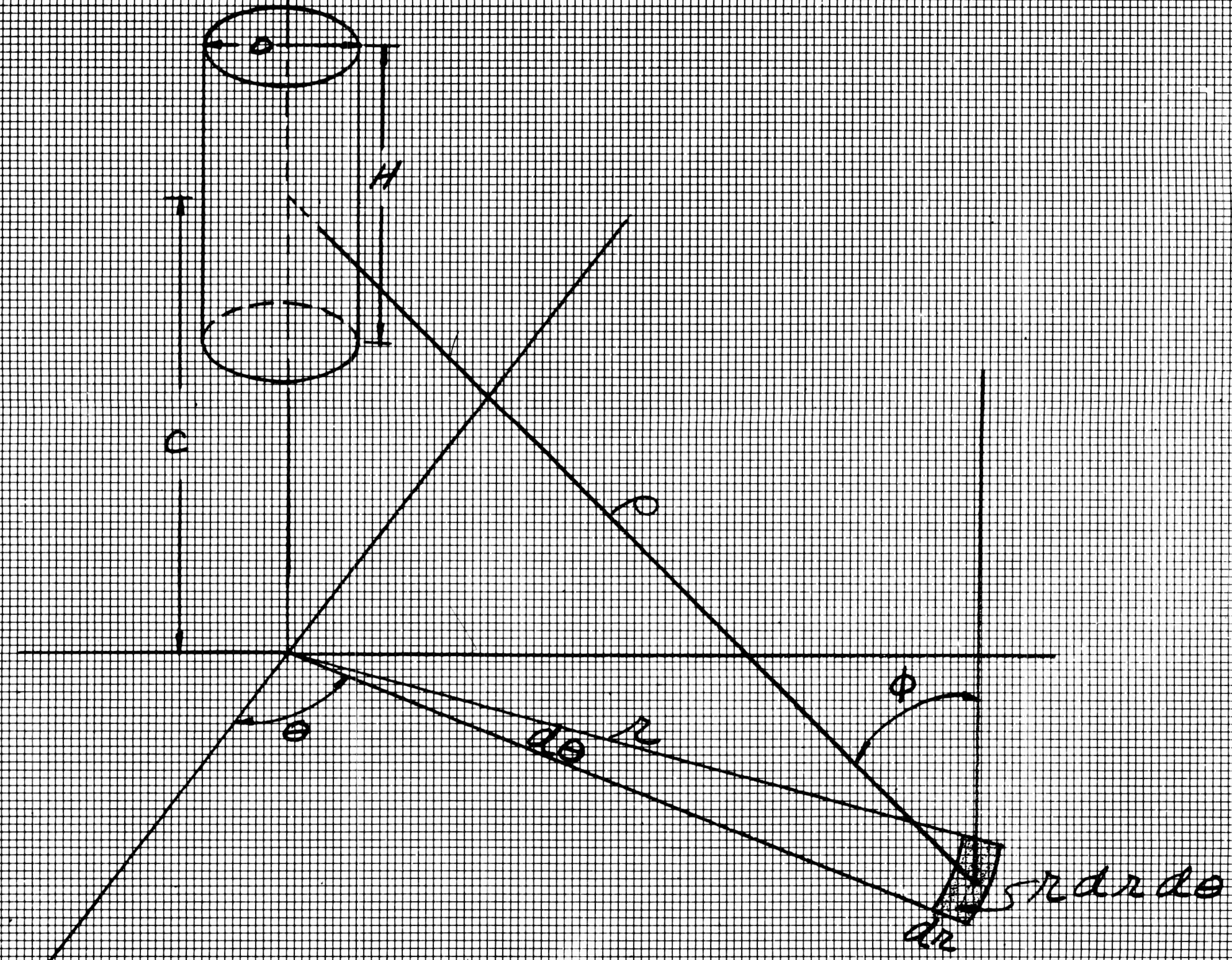


FIG 3

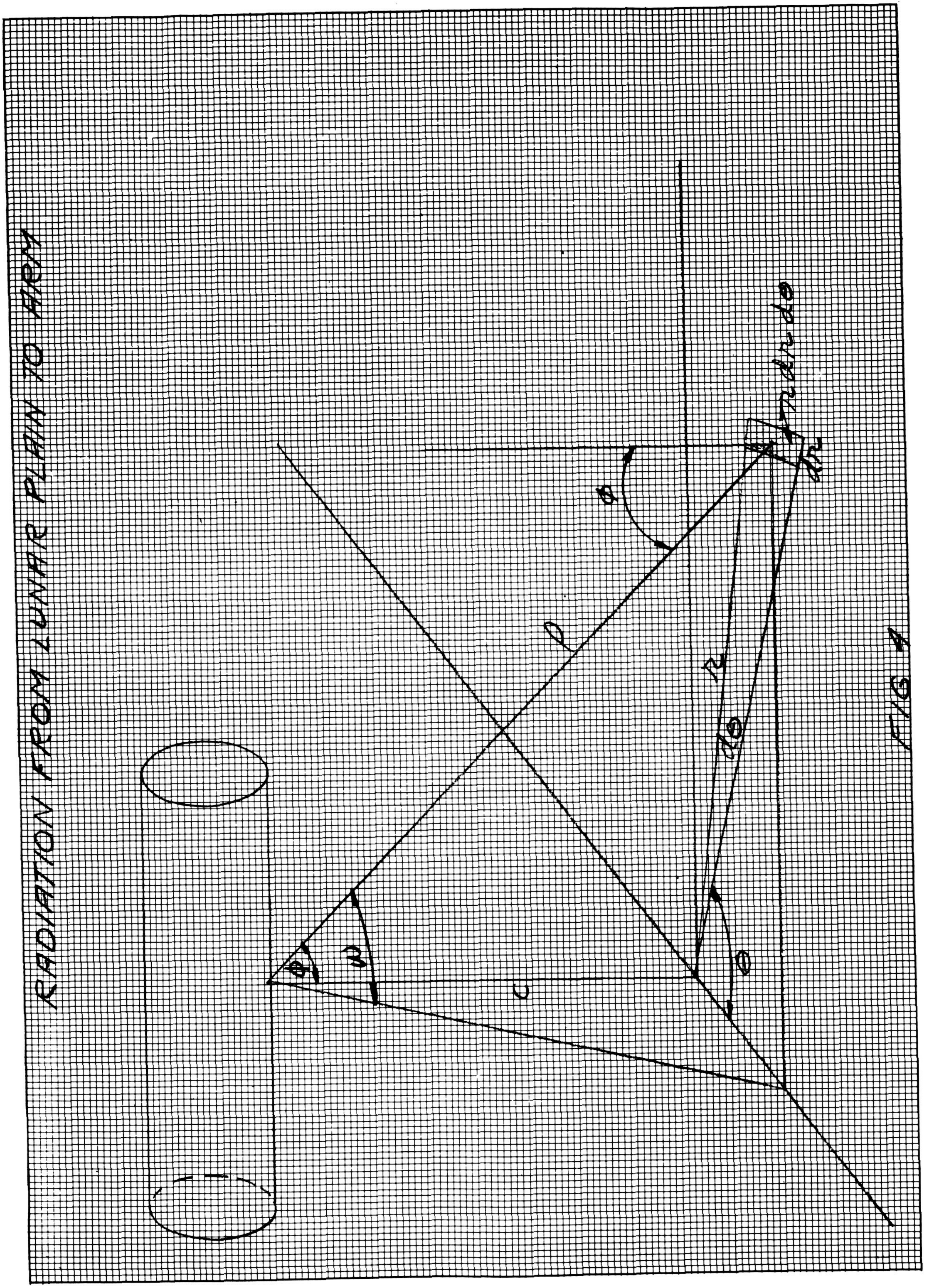


FIG 4

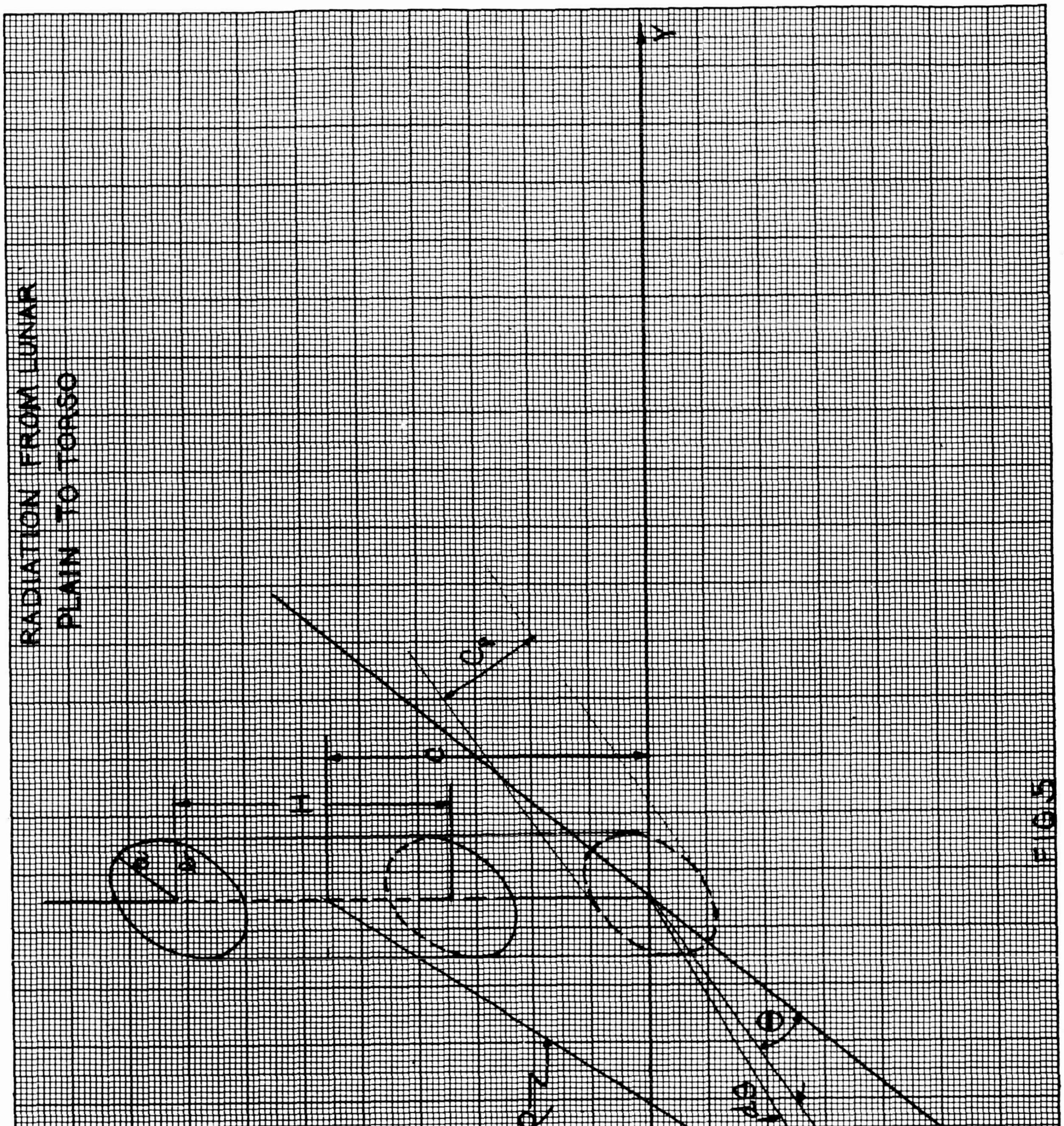


FIG 5

RADIATION FROM LUNAR PLAIN TO LEGS

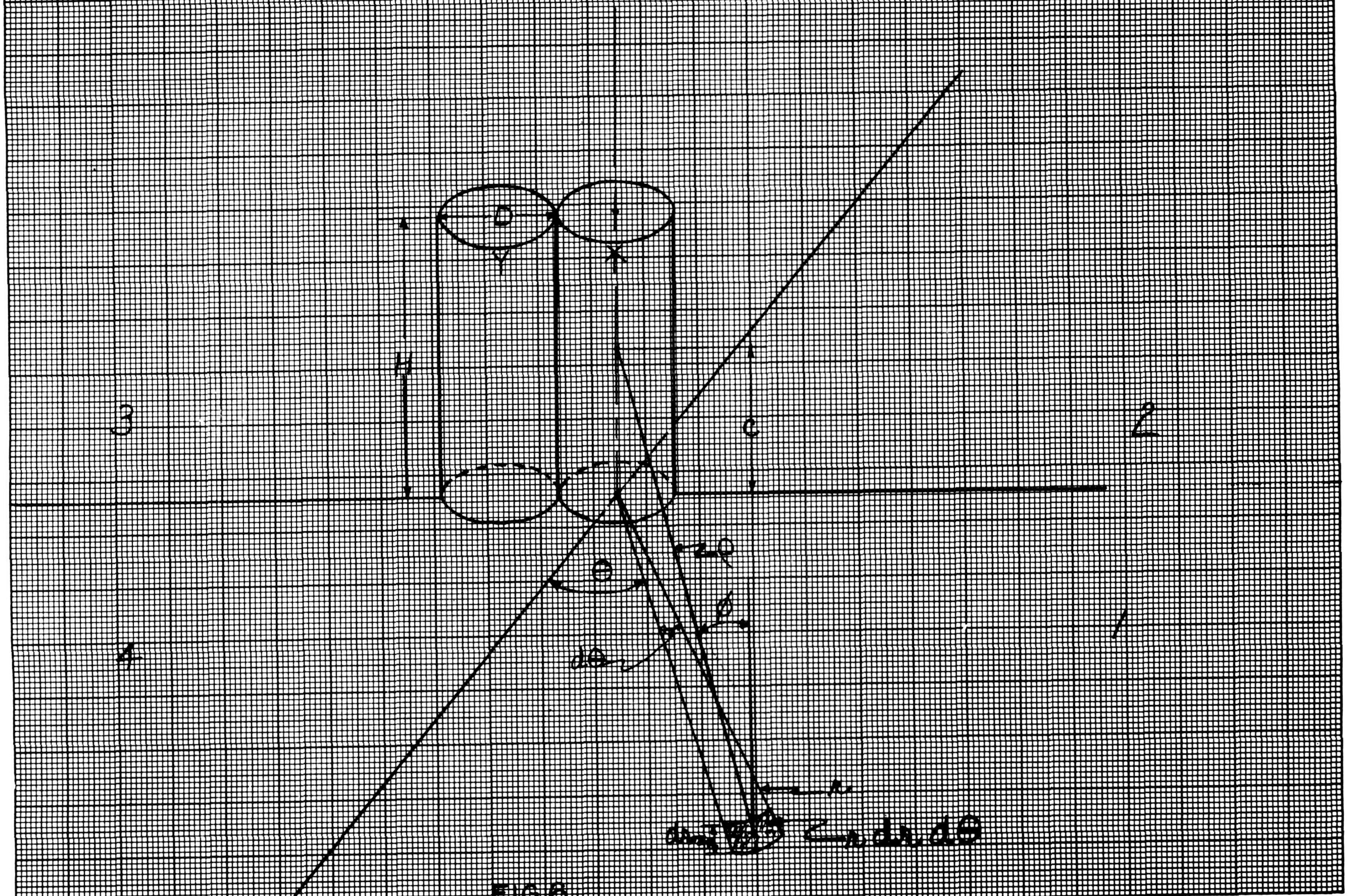


FIG 6

RADIATION FROM LUNAR PLAIN
TO CYLINDER-HEMISPHERE MAN

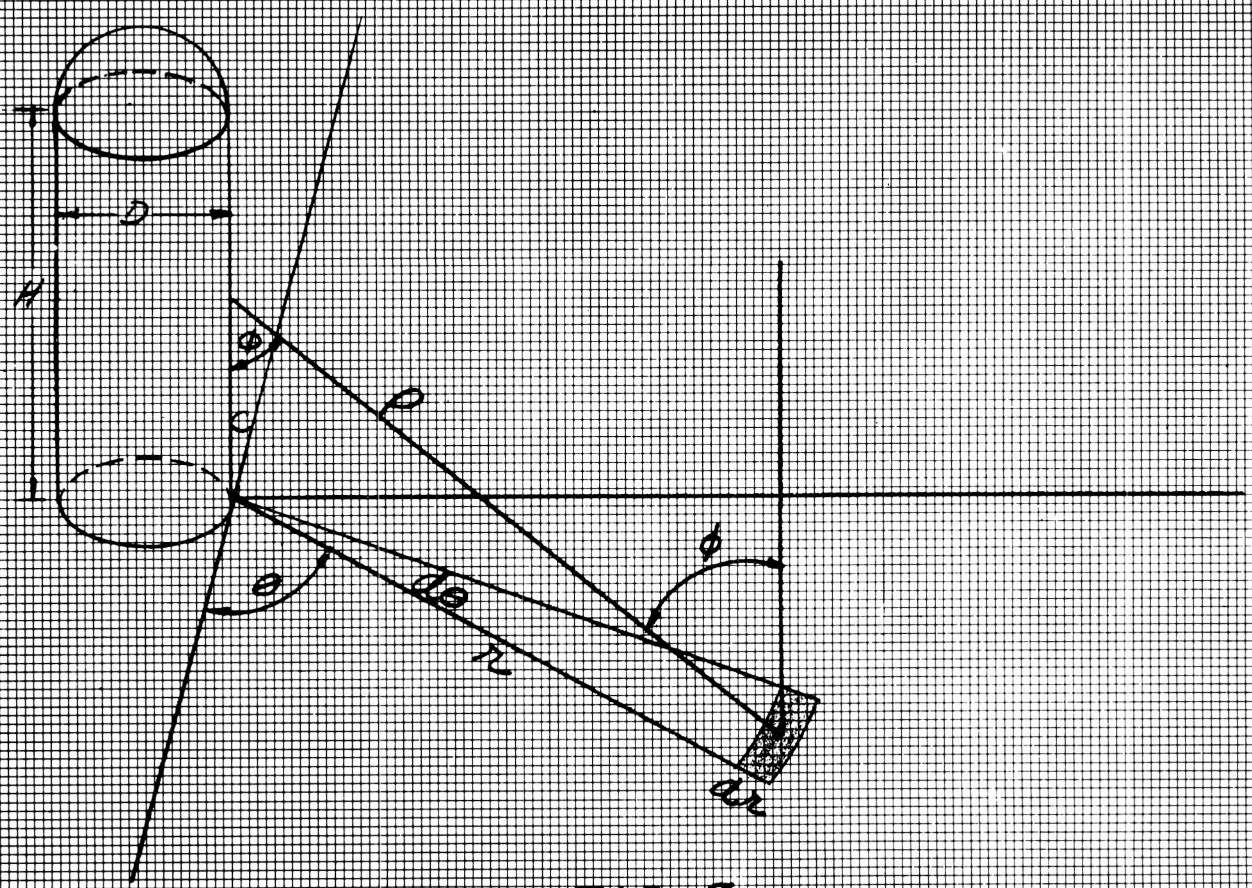


FIG 7

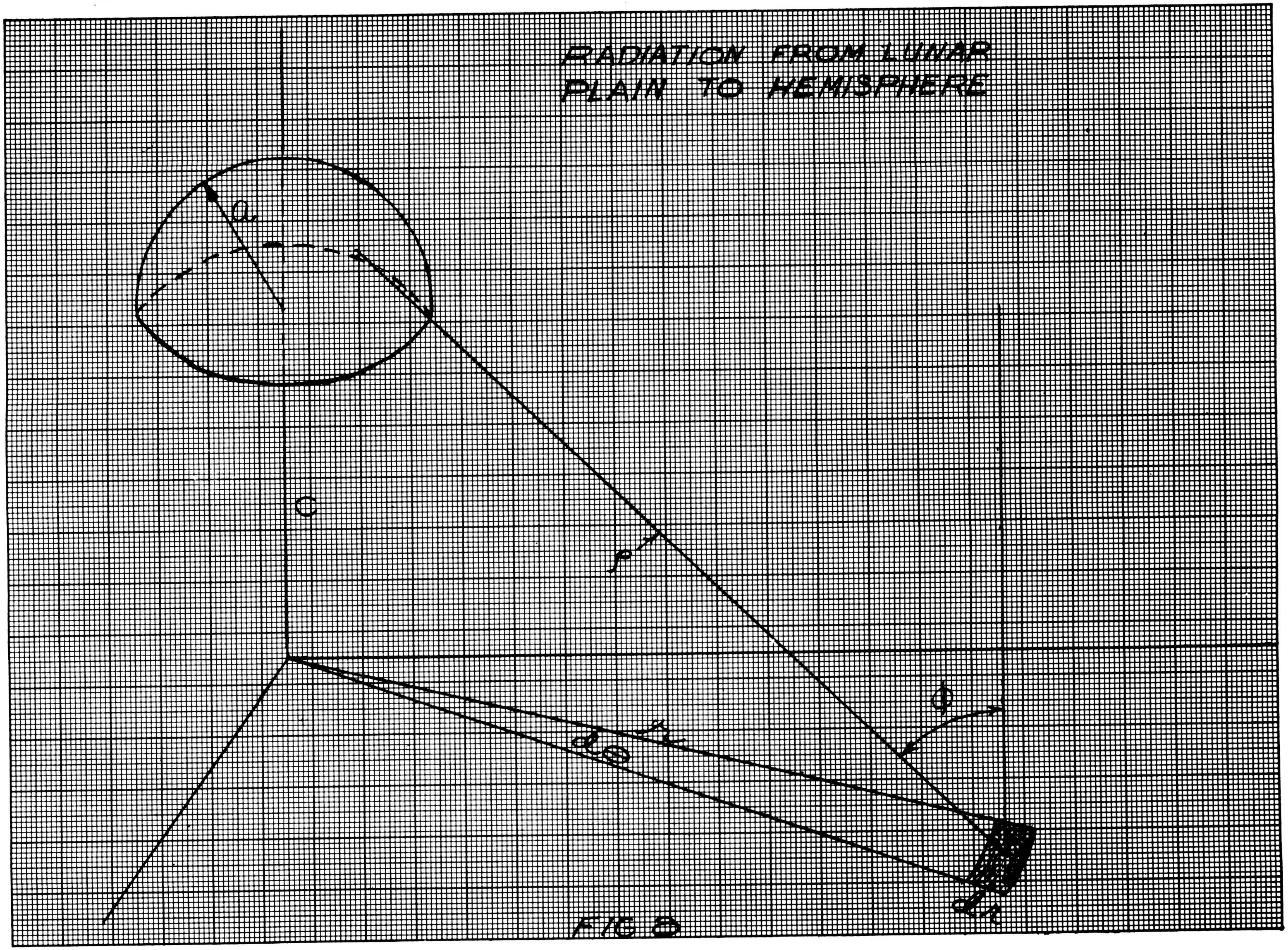


FIG 8

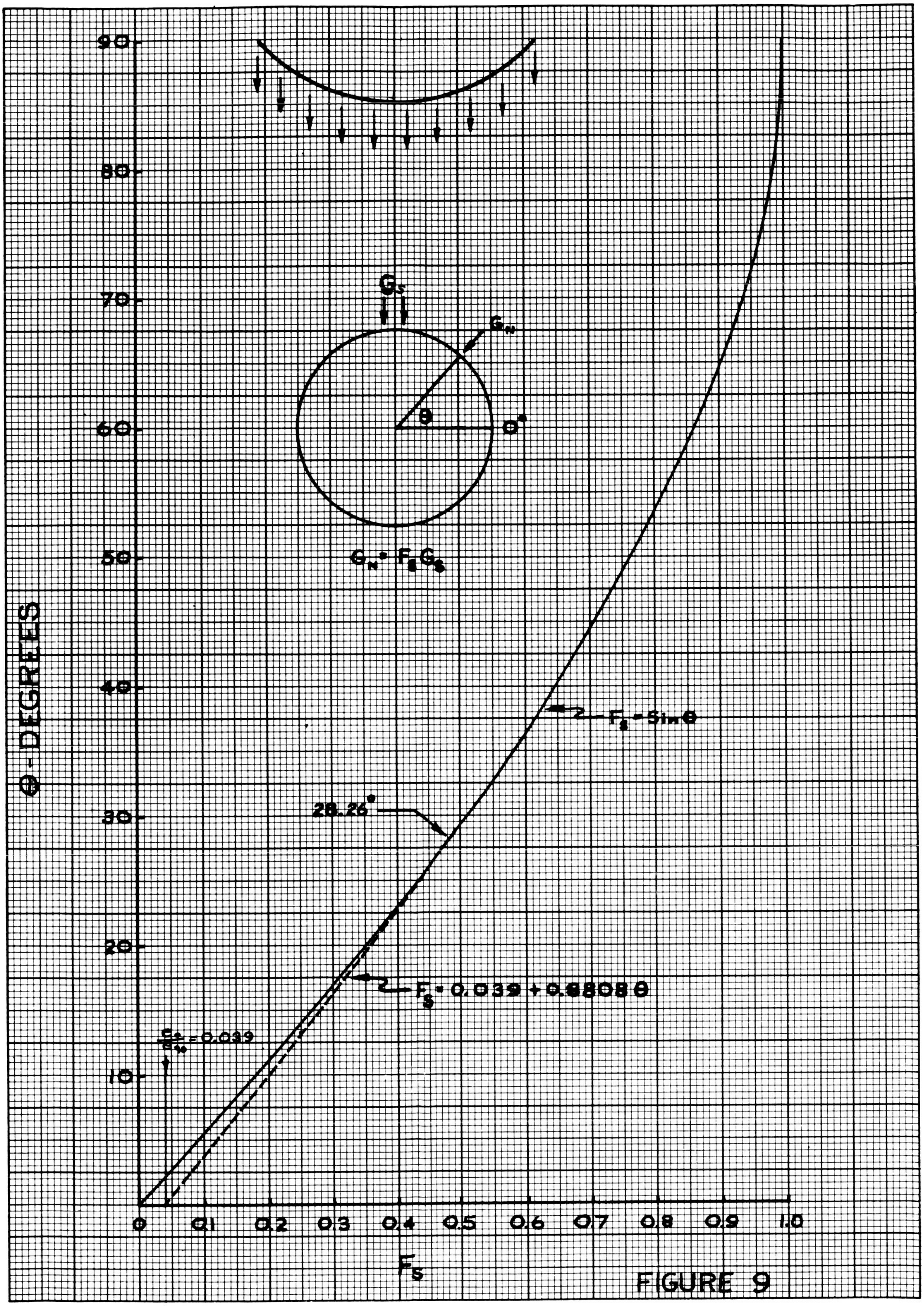

θ - DEGREES
90
80
70
60
50
40
30
20
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
F_S
G_S
G_N
θ
0°
$G_N = F_S G_S$
$F_S = \sin\theta$
28.26°
$F_S = 0.039 + 0.8808\,\theta$
0.039

FIGURE 9

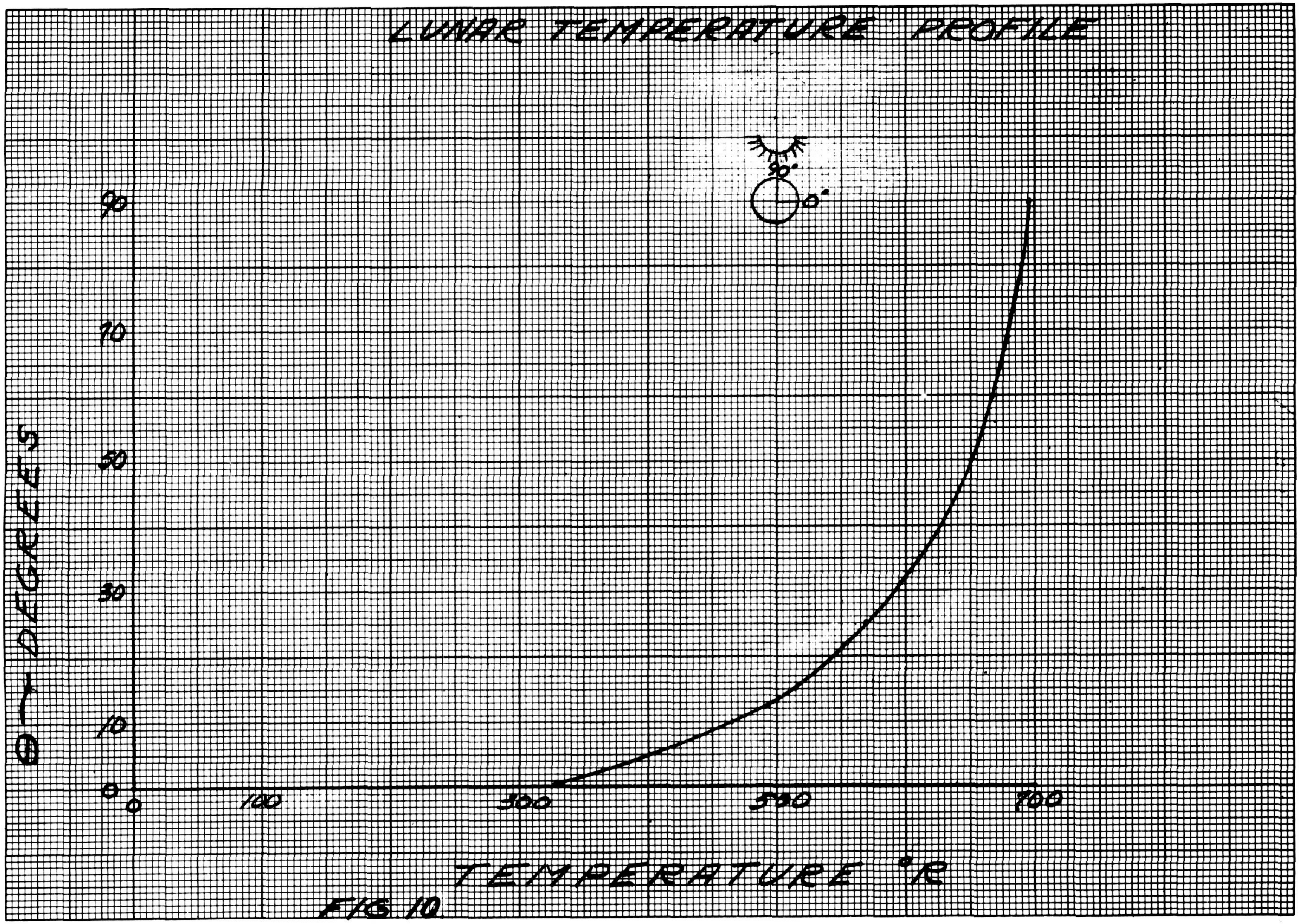
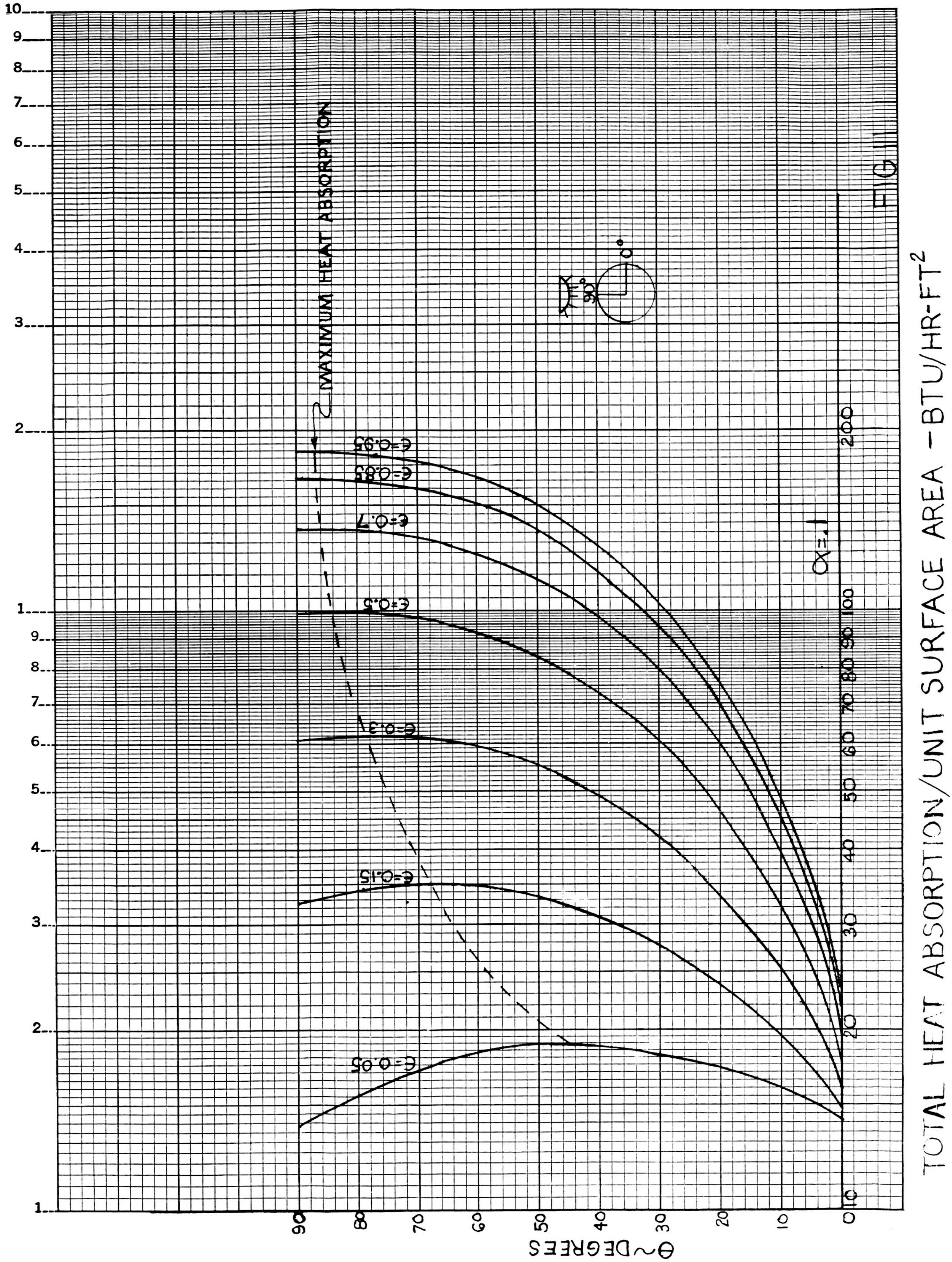

LUNAR TEMPERATURE PROFILE
90°
0°
90
70
50
30
10
0
0
100
300
500
700
θ — DEGREES
TEMPERATURE °R

FIG 10.


MAXIMUM HEAT ABSORPTION
ε=0.95
ε=0.85
ε=0.7
ε=0.5
ε=0.3
ε=0.15
ε=0.05
α=.1
90°
0°
θ~DEGREES
TOTAL HEAT ABSORPTION/UNIT SURFACE AREA - BTU/HR-FT²
FIG 11

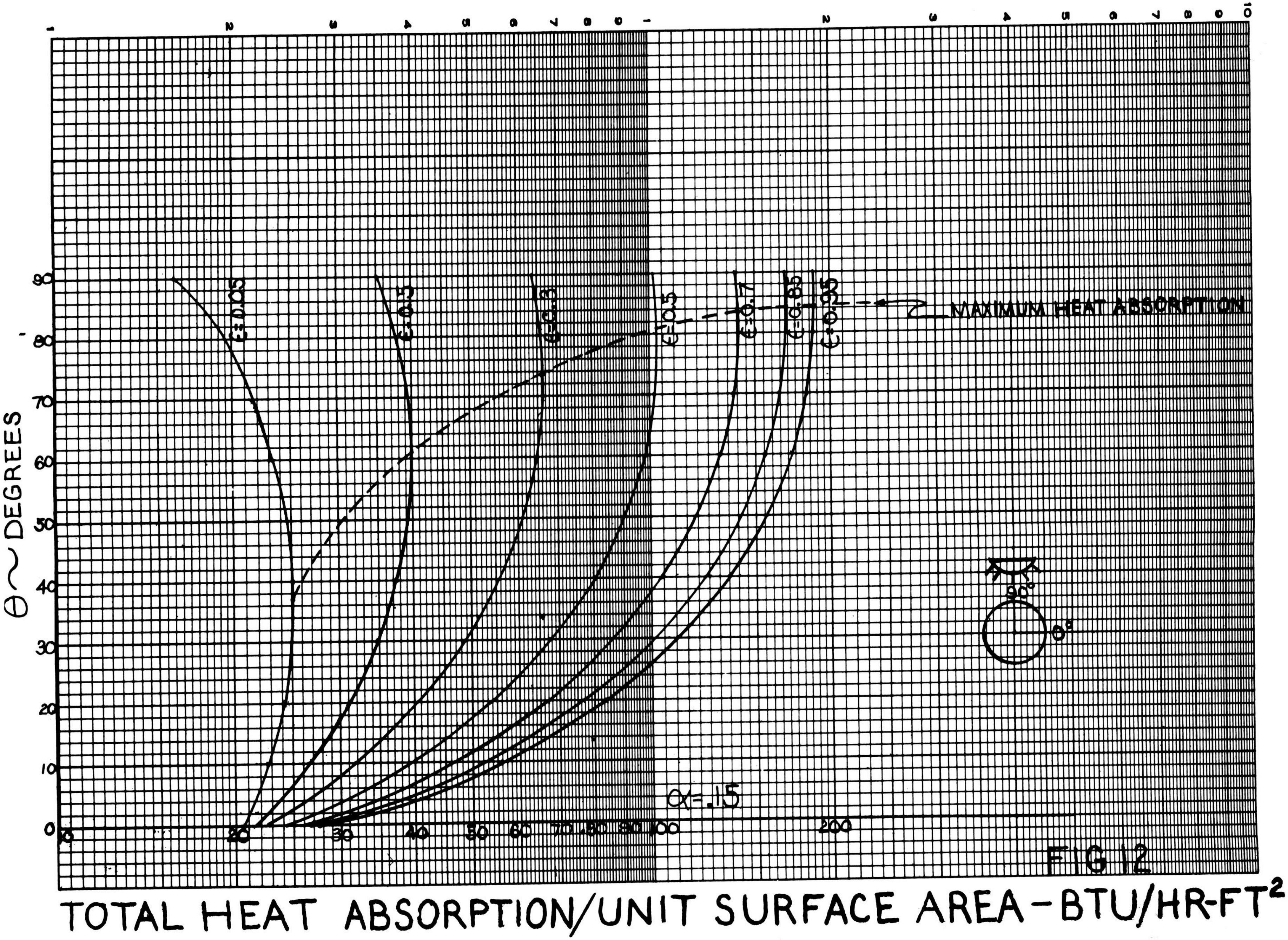

MAXIMUM HEAT ABSORPTION
ε=0.05
ε=0.15
ε=0.3
ε=0.5
ε=0.7
ε=0.85
ε=0.95
α=.15
90°
0°
θ ~ DEGREES
TOTAL HEAT ABSORPTION/UNIT SURFACE AREA - BTU/HR-FT²

FIG 12

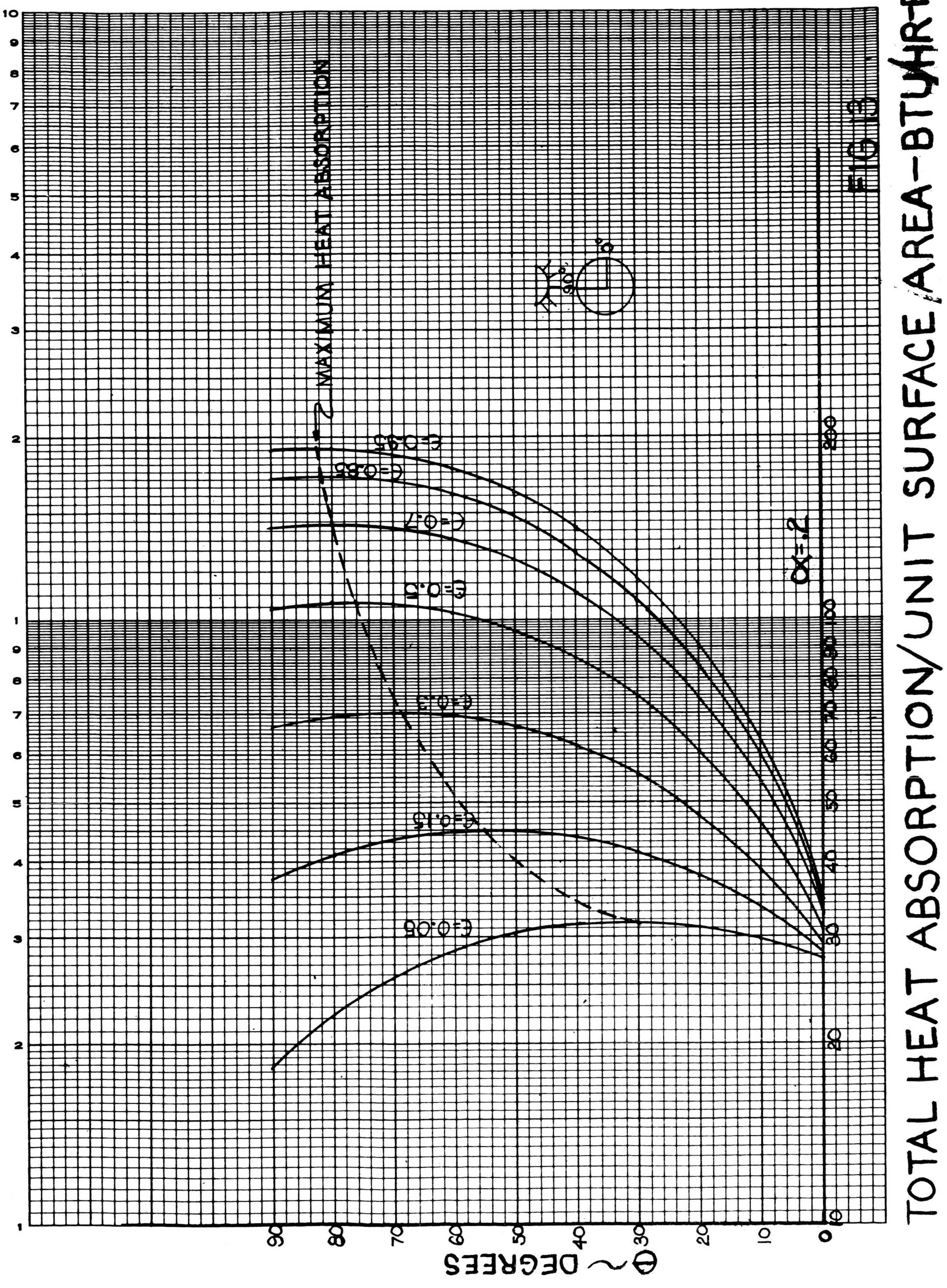

MAXIMUM HEAT ABSORPTION
ε=0.95
ε=0.85
ε=0.7
ε=0.5
ε=0.3
ε=0.15
ε=0.05
α=.2
90°
0°
Θ ~ DEGREES
TOTAL HEAT ABSORPTION/UNIT SURFACE AREA-BTU/HR-FT²

FIG 13

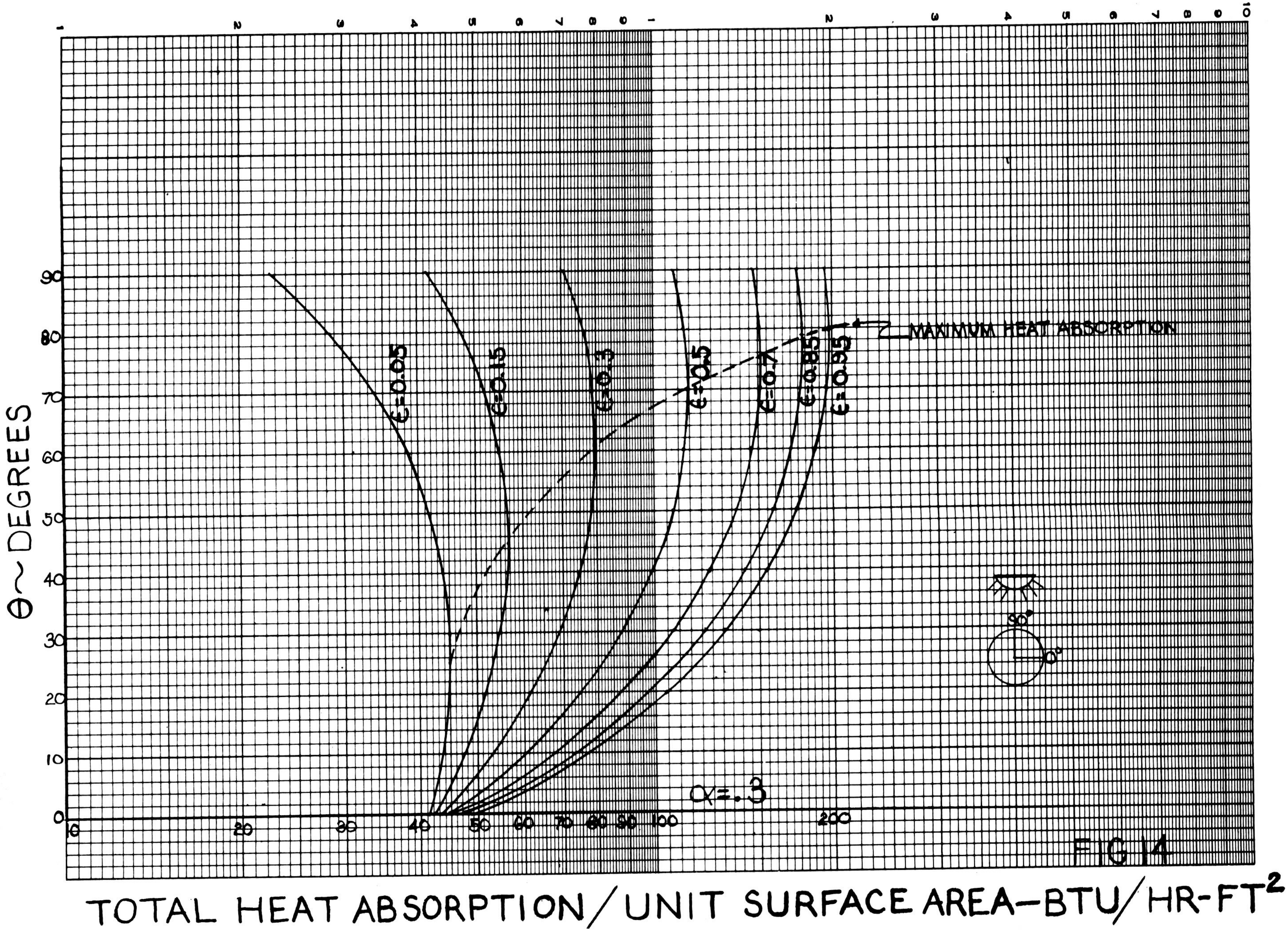

θ ~ DEGREES
TOTAL HEAT ABSORPTION/UNIT SURFACE AREA–BTU/HR-FT^2
MAXIMUM HEAT ABSORPTION
ε=0.05
ε=0.15
ε=0.3
ε=0.5
ε=0.7
ε=0.85
ε=0.95
α=.3
90°
0°

FIG 14

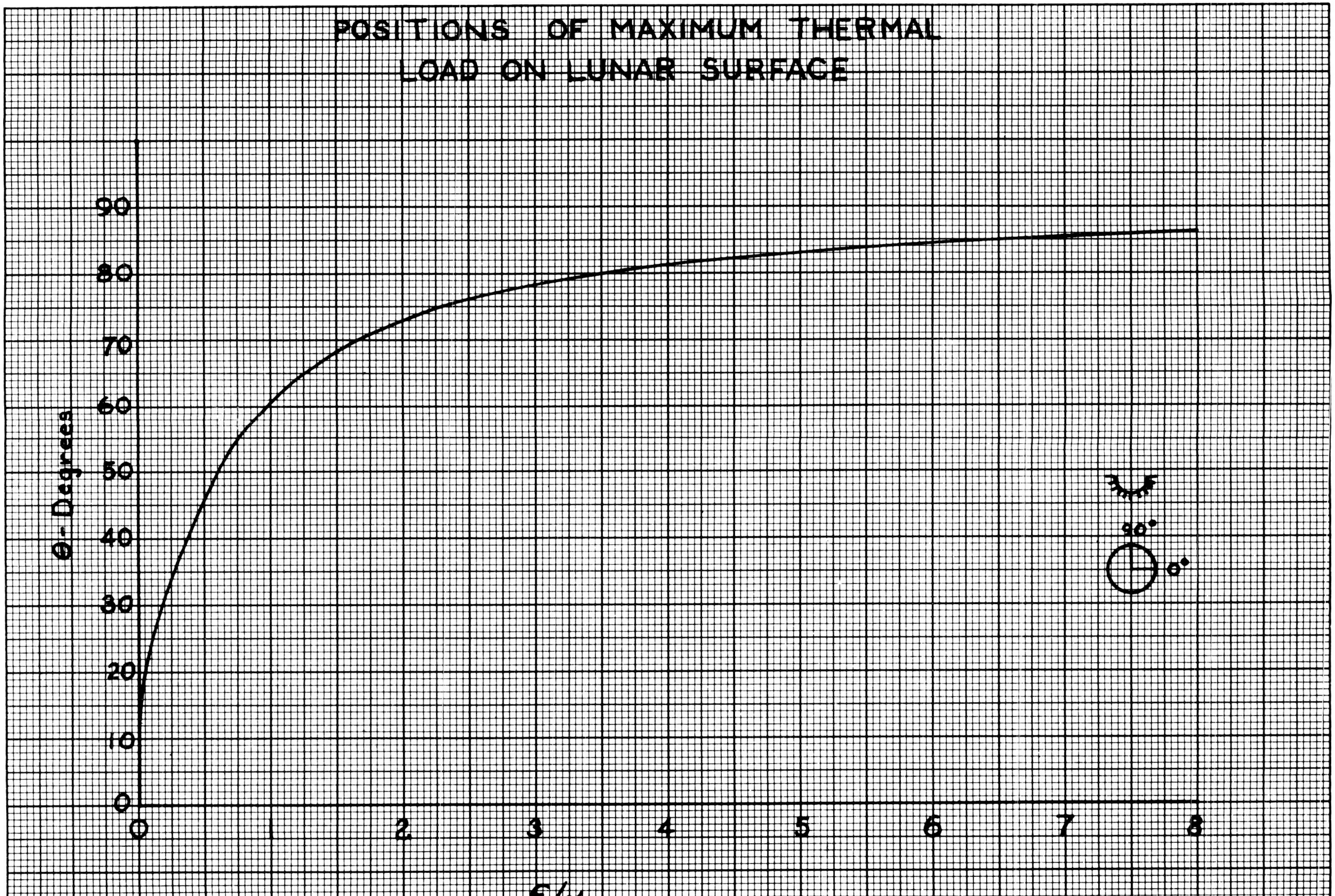

POSITIONS OF MAXIMUM THERMAL
LOAD ON LUNAR SURFACE
θ - Degrees
0
10
20
30
40
50
60
70
80
90
0
1
2
3
4
5
6
7
8
ϵ/α_s
90°
0°

FIGURE 15

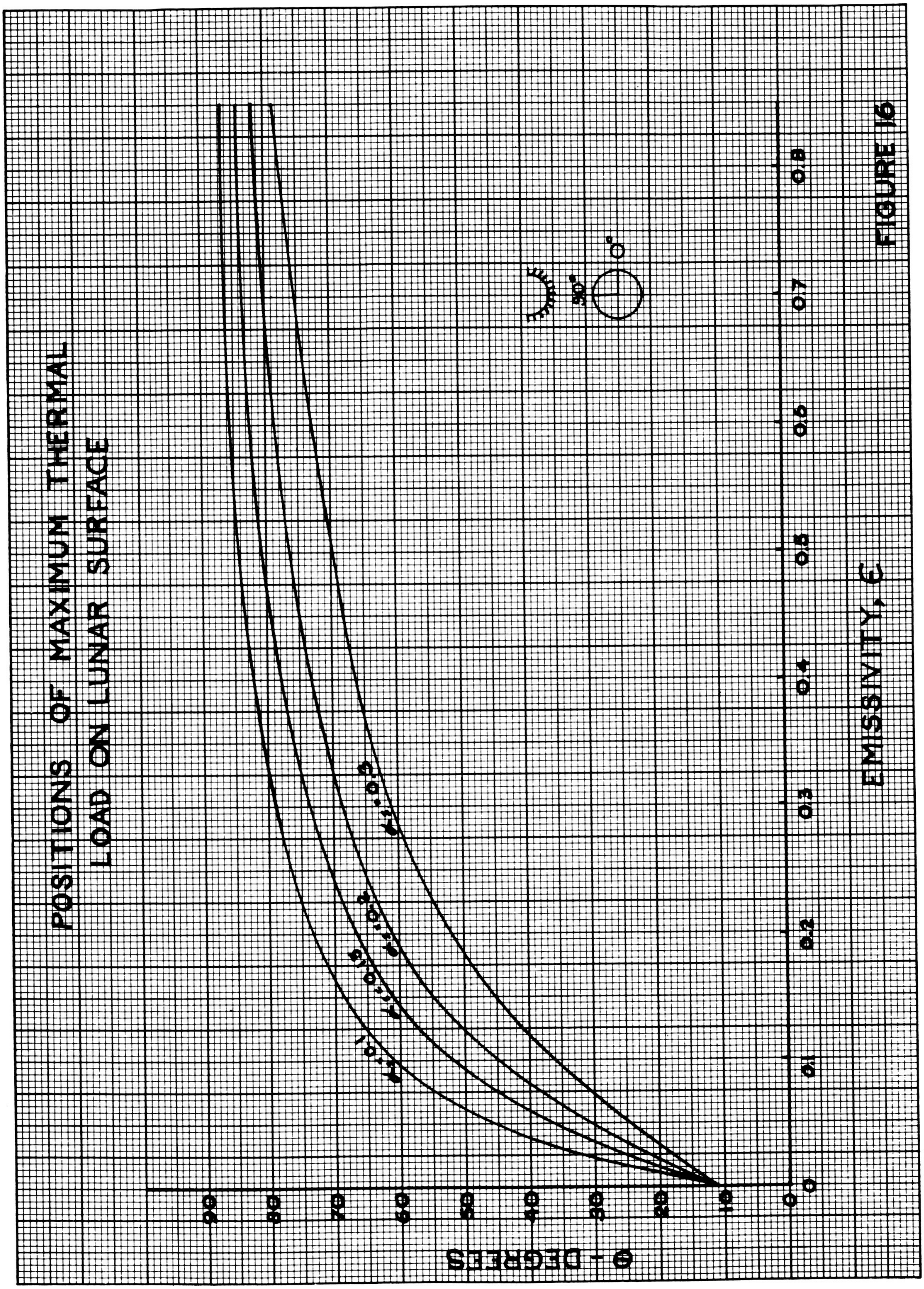

POSITIONS OF MAXIMUM THERMAL
LOAD ON LUNAR SURFACE
θ - DEGREES
0
10
20
30
40
50
60
70
80
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
EMISSIVITY, ϵ
$\alpha_s = 0.1$
$\alpha_s = 0.15$
$\alpha_s = 0.2$
$\alpha_s = 0.3$
90°
0°

FIGURE 16

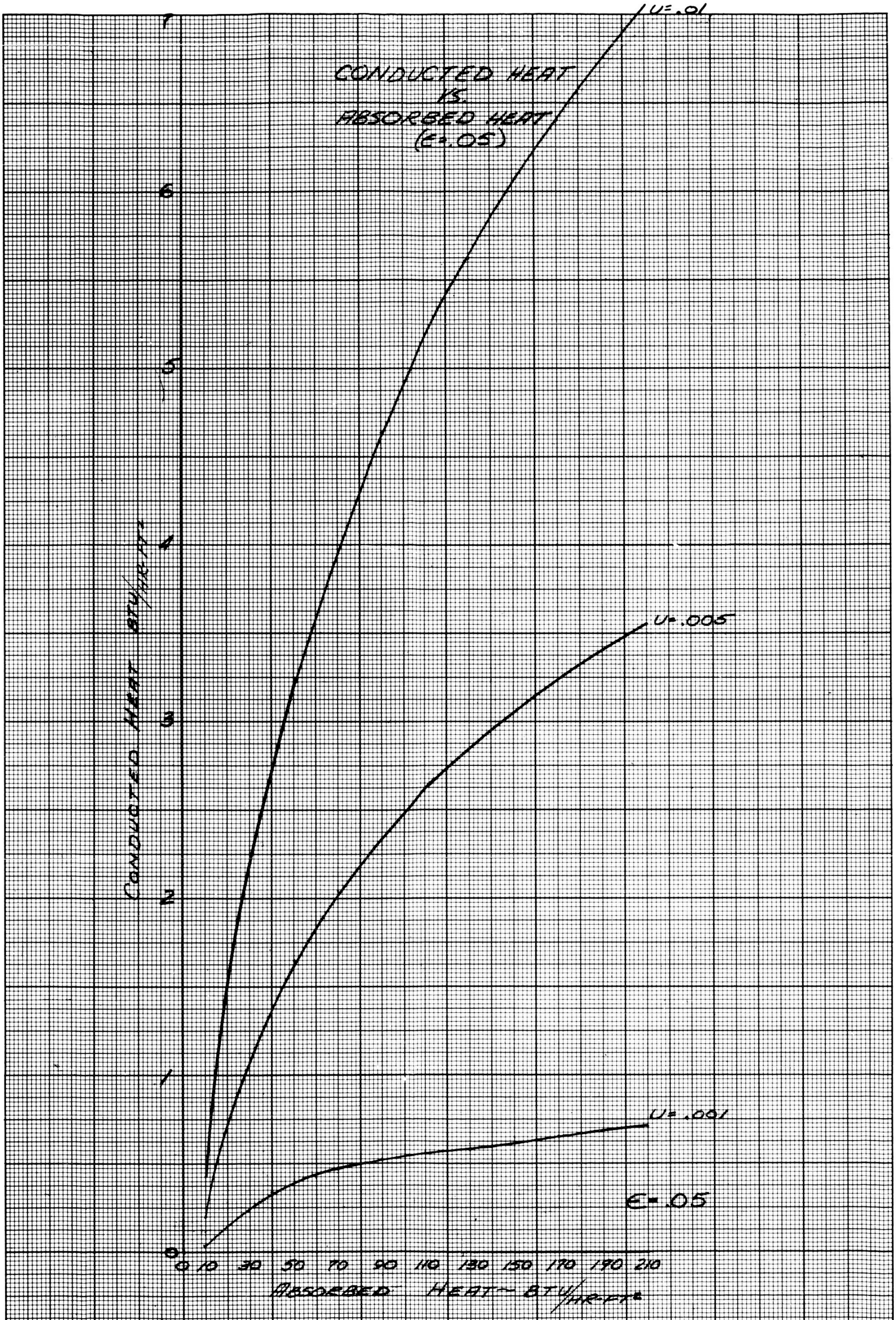

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E=.05)
U=.01
U=.005
U=.001
E=.05
CONDUCTED HEAT BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
0
1
2
3
4
5
6
7
0 10 30 50 70 90 110 130 150 170 190 210

FIG 17

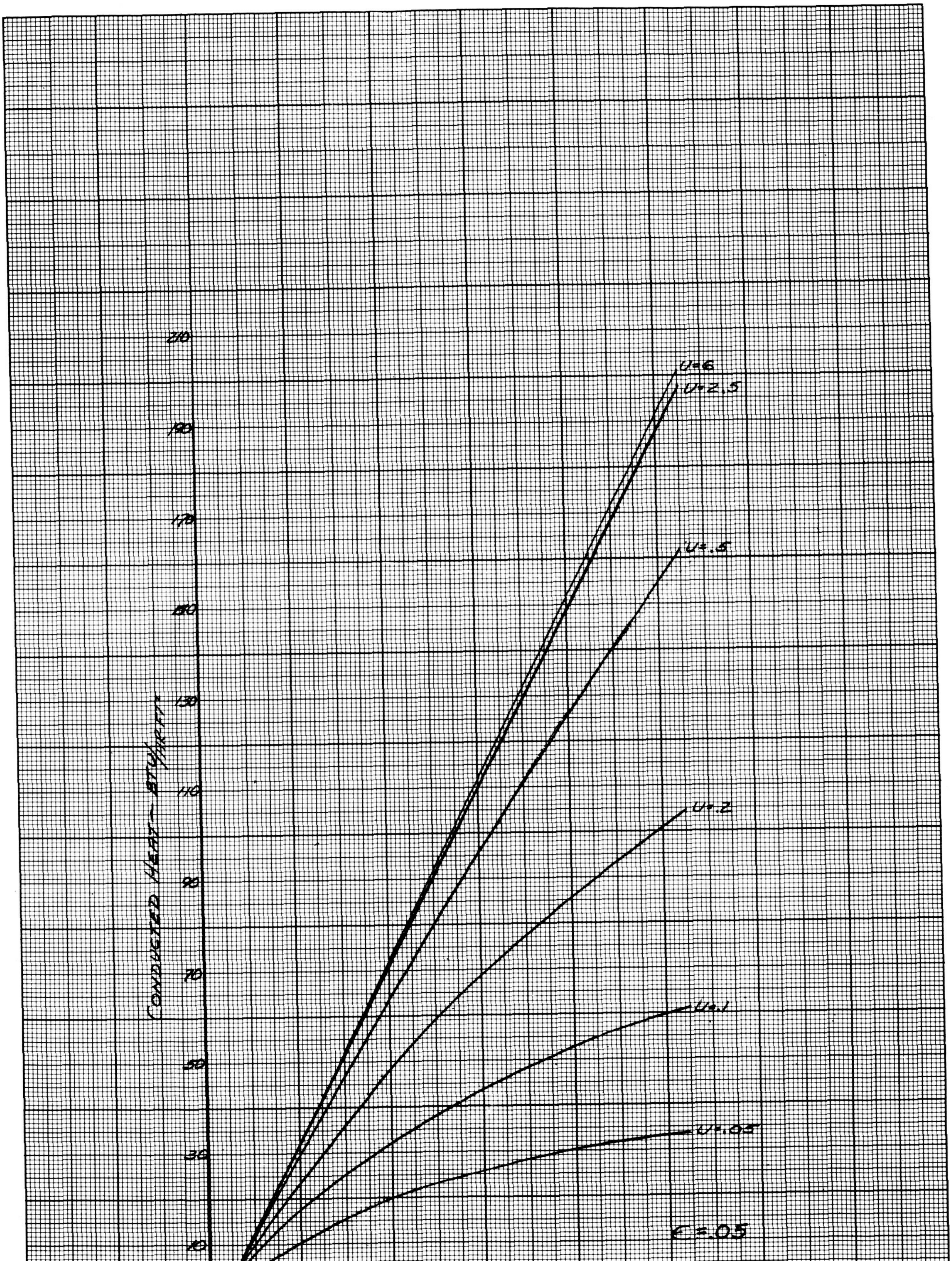

U=6
U=2.5
U=.5
U=.2
U=.1
U=.05
∈=.05
CONDUCTED HEAT — BTU/HR FT²
ABSORBED HEAT — BTU/HR FT²
0
10
30
50
70
90
110
130
150
170
190
210

FIG 17A

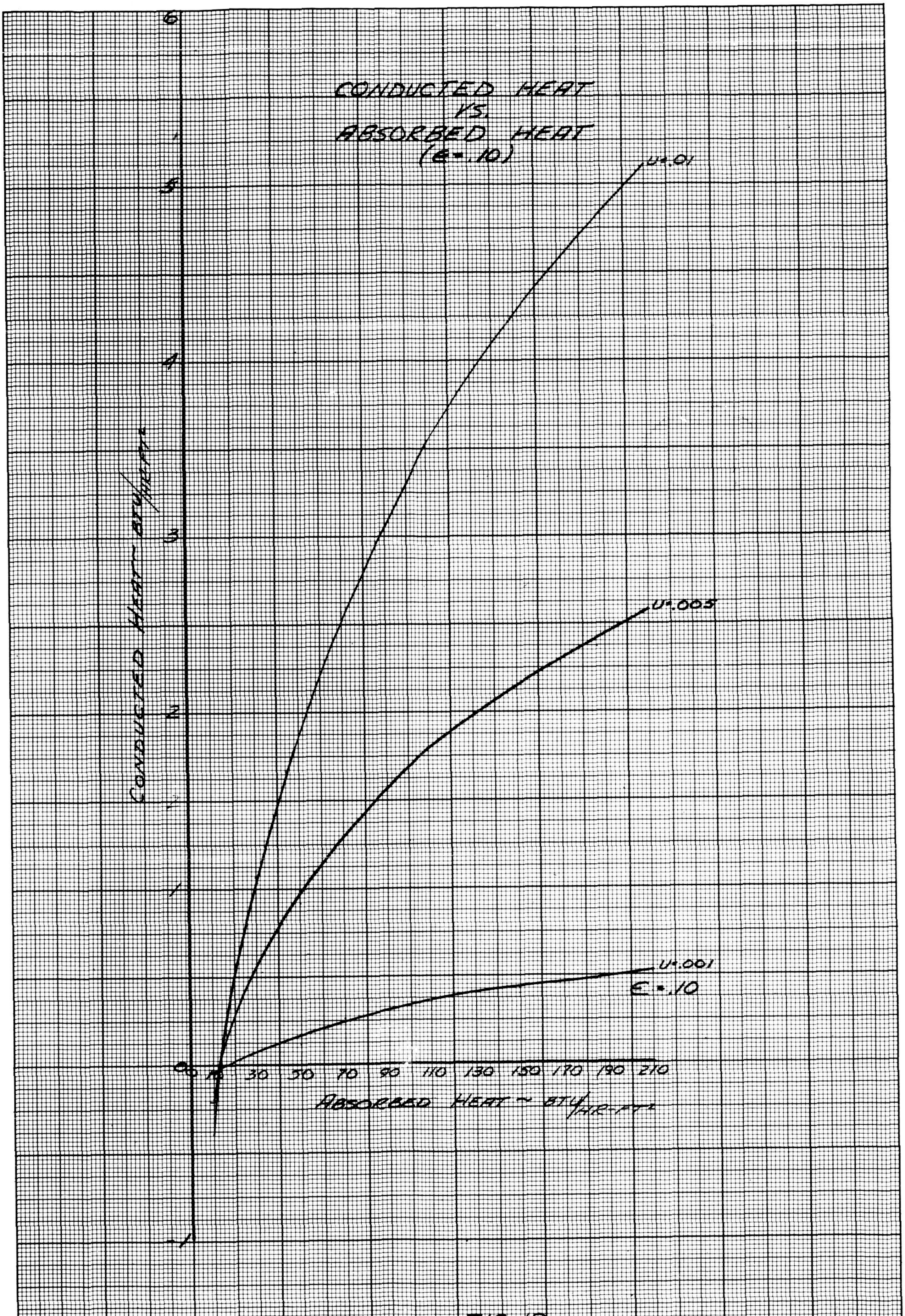
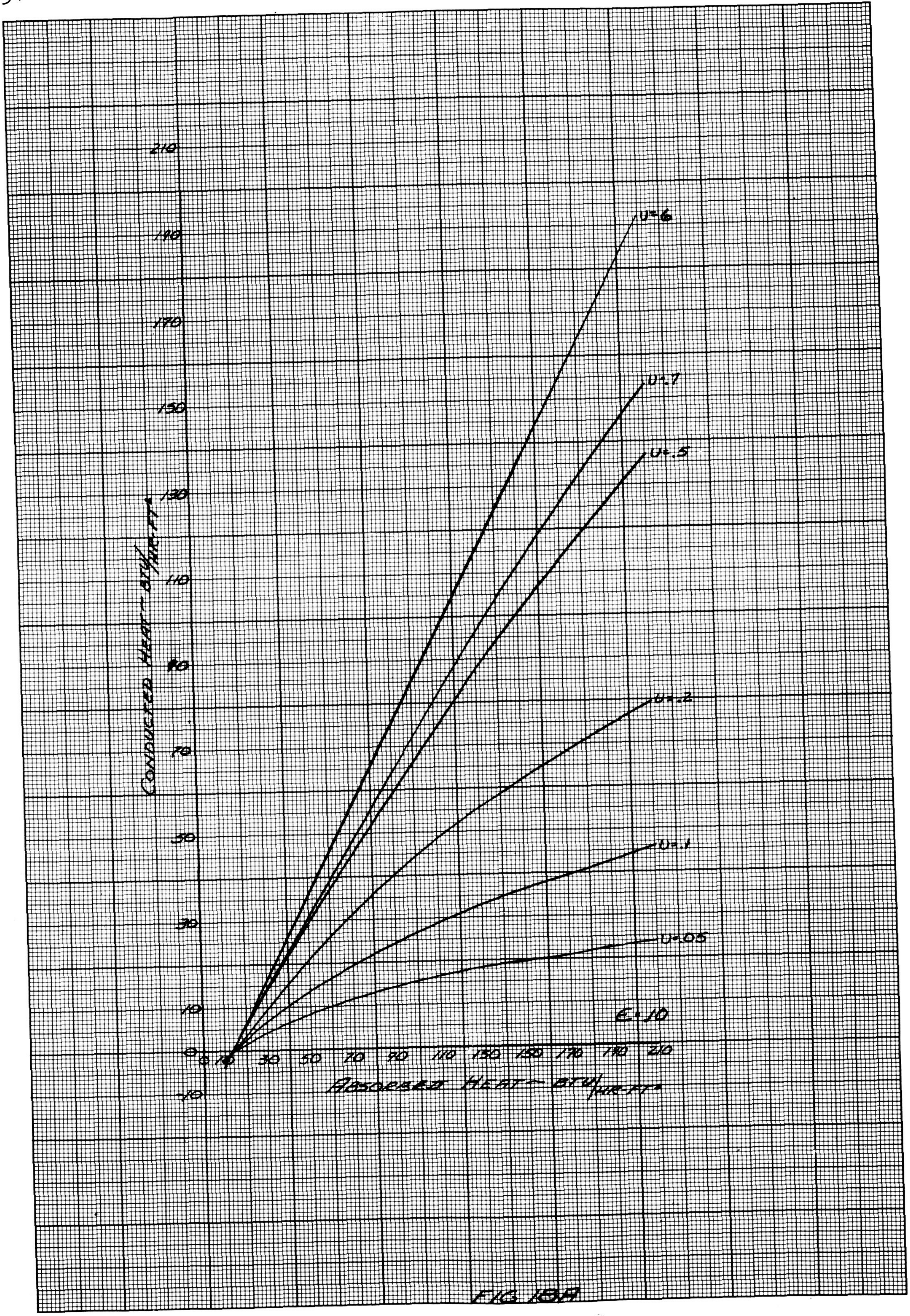

CONDUCTED HEAT
VS.
ABSORBED HEAT
(ε=.10)
U=.01
U=.005
U=.001
ε=.10
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
0
10
30
50
70
90
110
130
150
170
190
210
6
5
4
3
2
1
-1

FIG 18



210
190
170
150
130
110
90
70
50
30
10
0
-10
CONDUCTED HEAT – BTU/HR-FT²
U=6
U=.7
U=.5
U=.2
U=.1
U=.05
E=.10
0
10
30
50
70
90
110
130
150
170
190
210
ABSORBED HEAT – BTU/HR-FT²

FIG. 18A

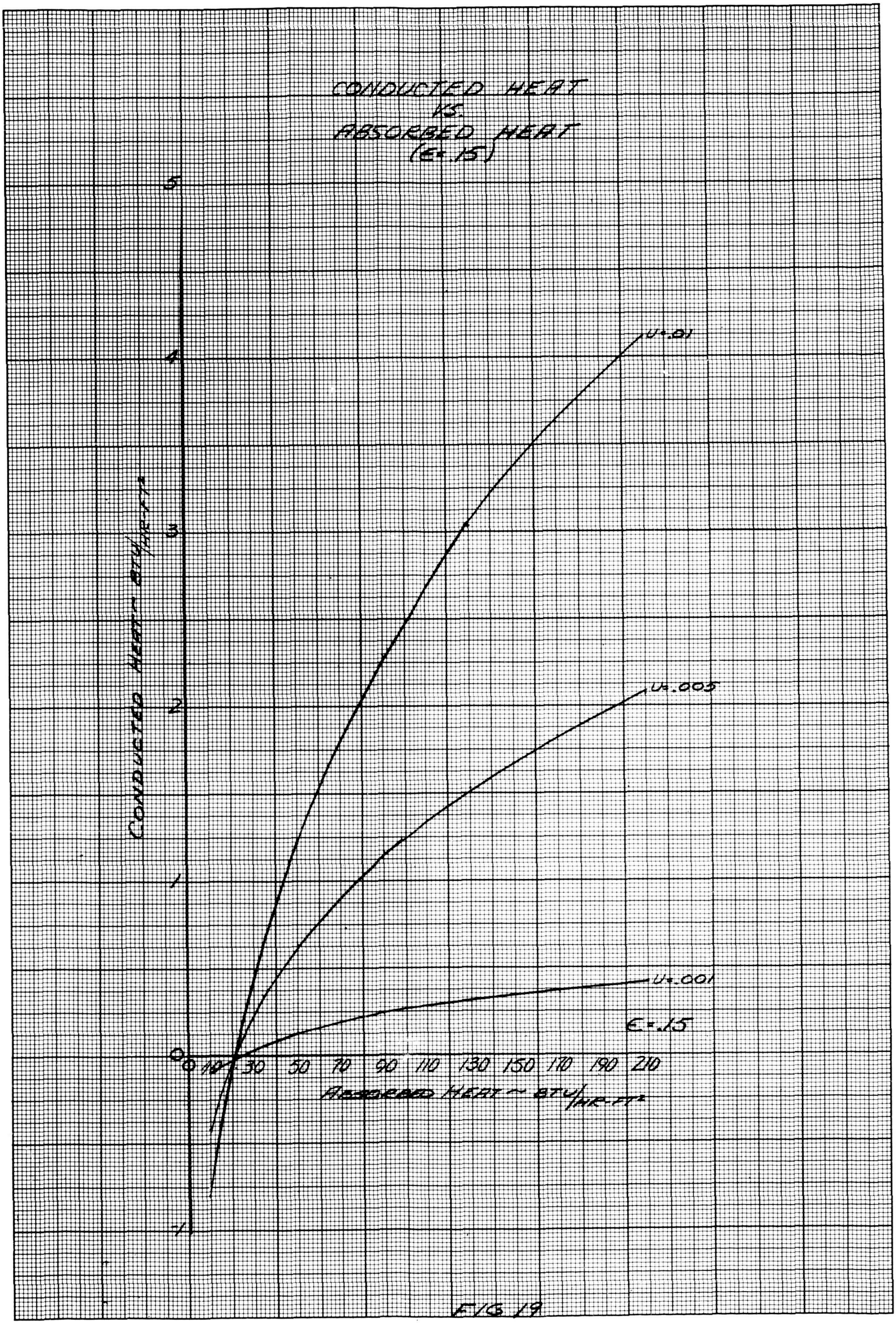
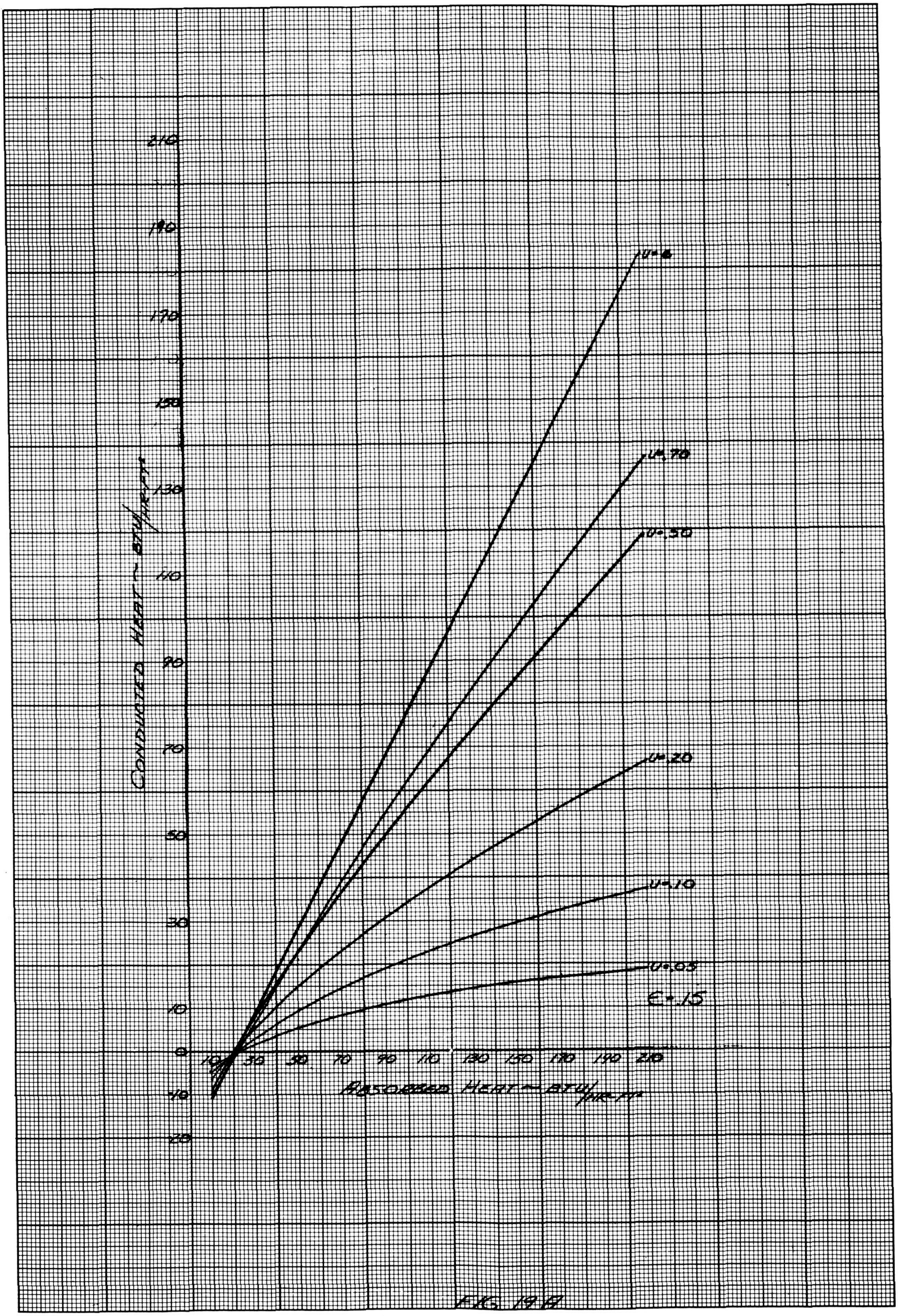

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E=.15)
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
U=.01
U=.005
U=.001
E=.15
5
4
3
2
1
0
-1
0
10
30
50
70
90
110
130
150
170
190
210

FIG 19



210
190
170
150
130
110
90
70
50
30
10
0
-10
-20
10
30
50
70
90
110
130
150
170
190
210
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
U=∞
U=.70
U=.50
U=.20
U=.10
U=.05
E=.15

FIG. 19 B

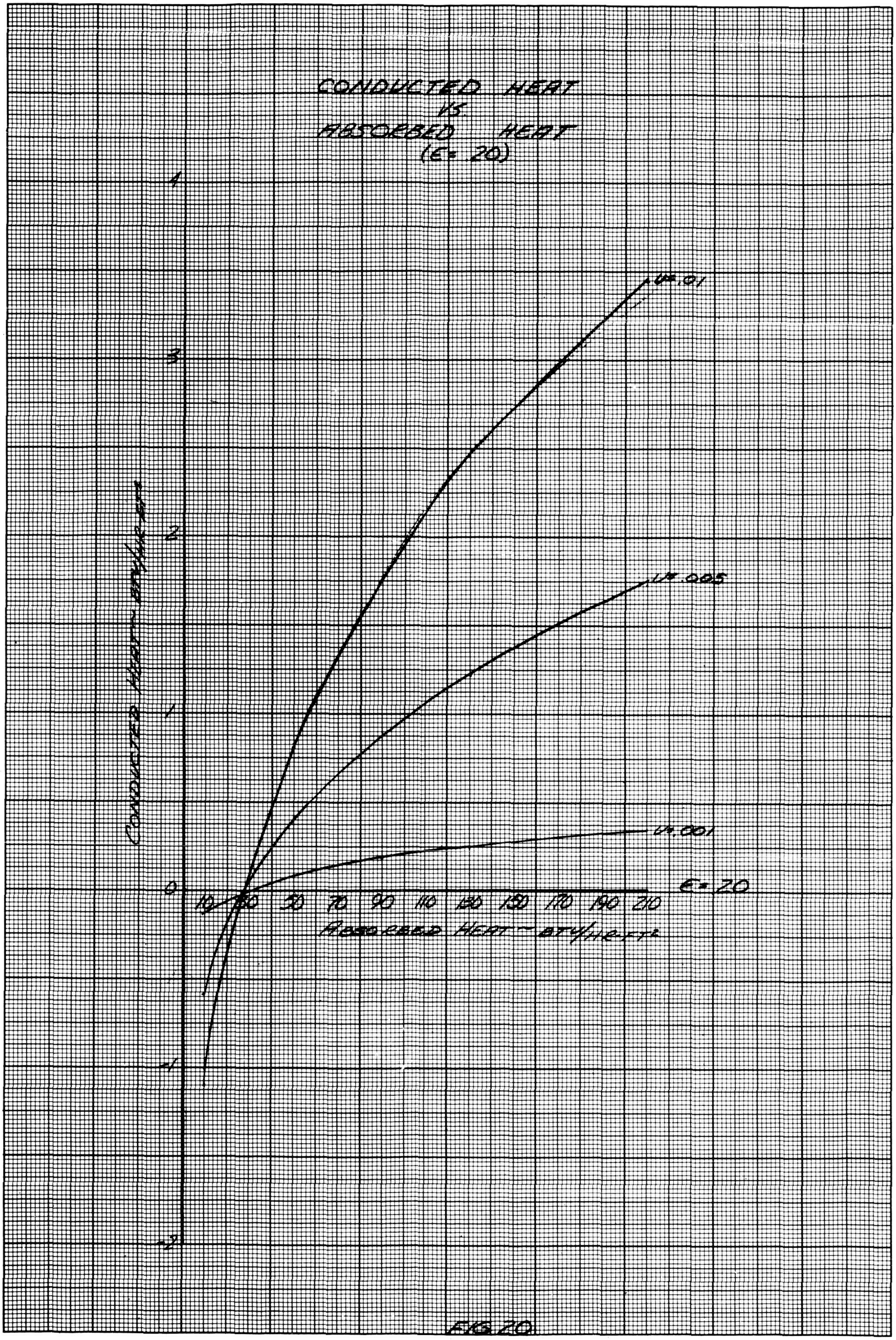

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E= 20)
U=.01
U=.005
U=.001
E=20
0
1
2
3
4
-1
-2
10
30
50
70
90
110
130
150
170
190
210
ABSORBED HEAT ~ BTU/HR FT²
CONDUCTED HEAT ~ BTU/HR FT²

FIG 20

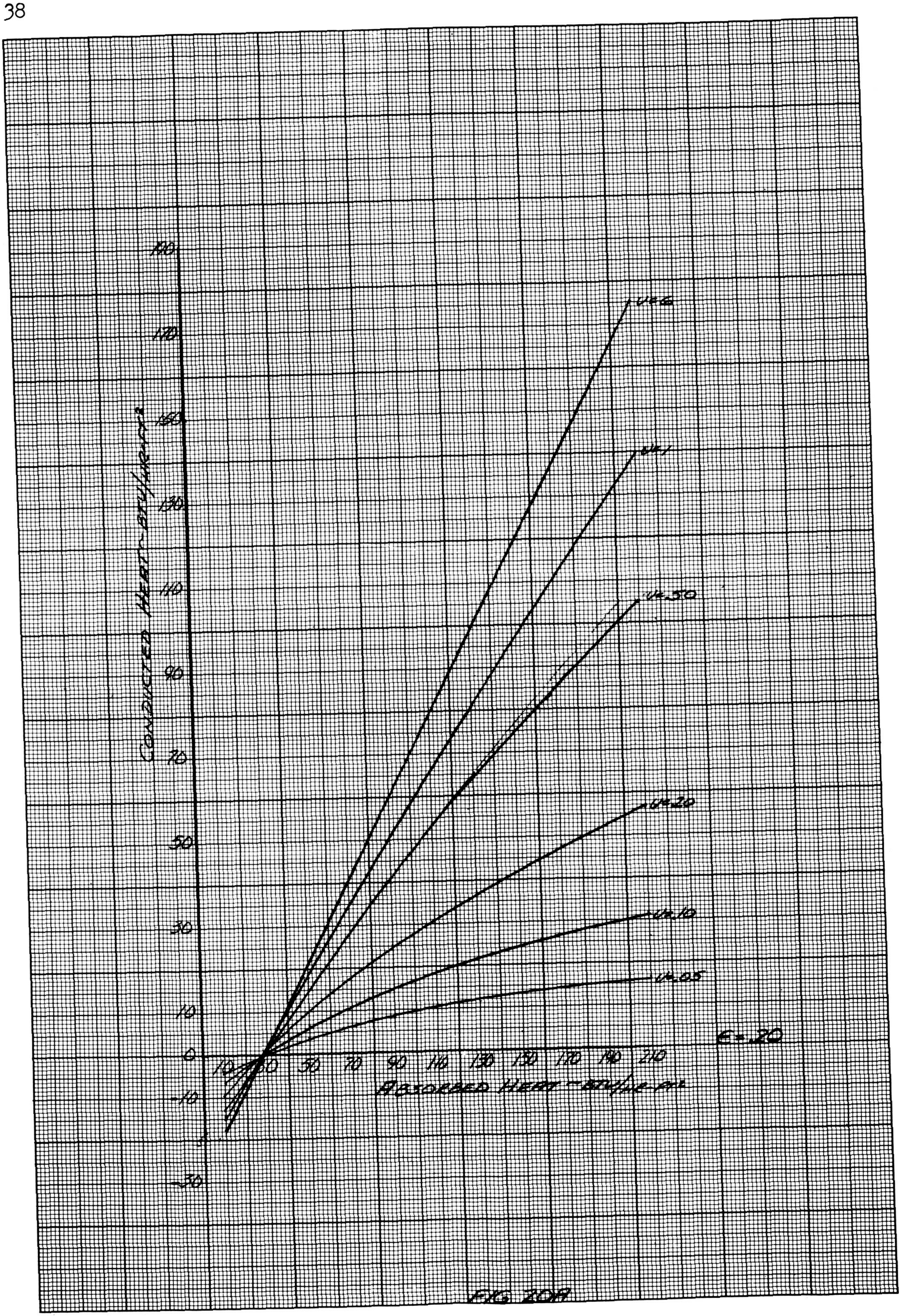

CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
E = .20
U=6
U=1
U=.50
U=.20
U=.10
U=.05

FIG 20A

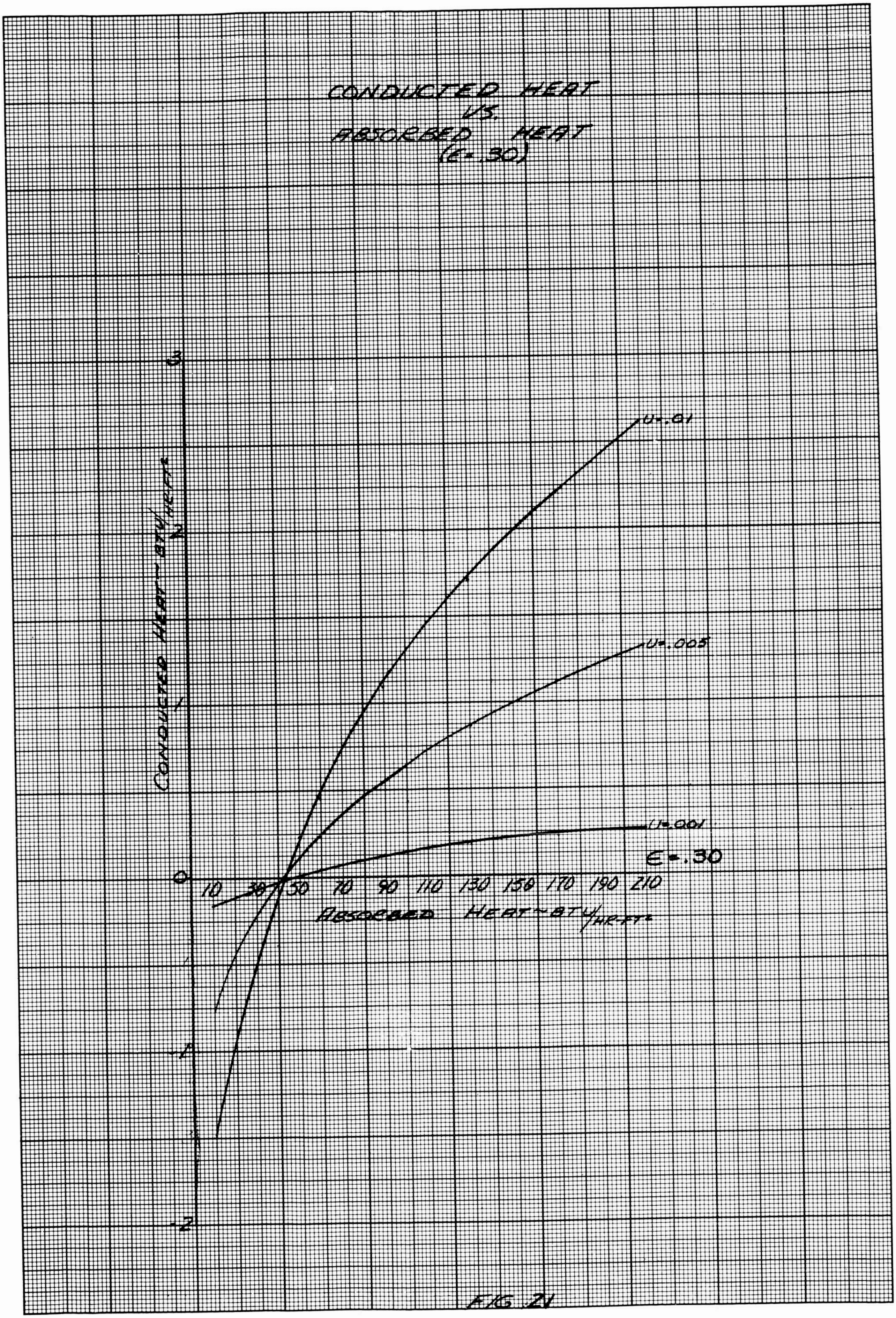

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E=.30)
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
U=.01
U=.005
U=.001
E=.30
3
2
1
0
-1
-2
10
30
50
70
90
110
130
150
170
190
210

FIG. 21

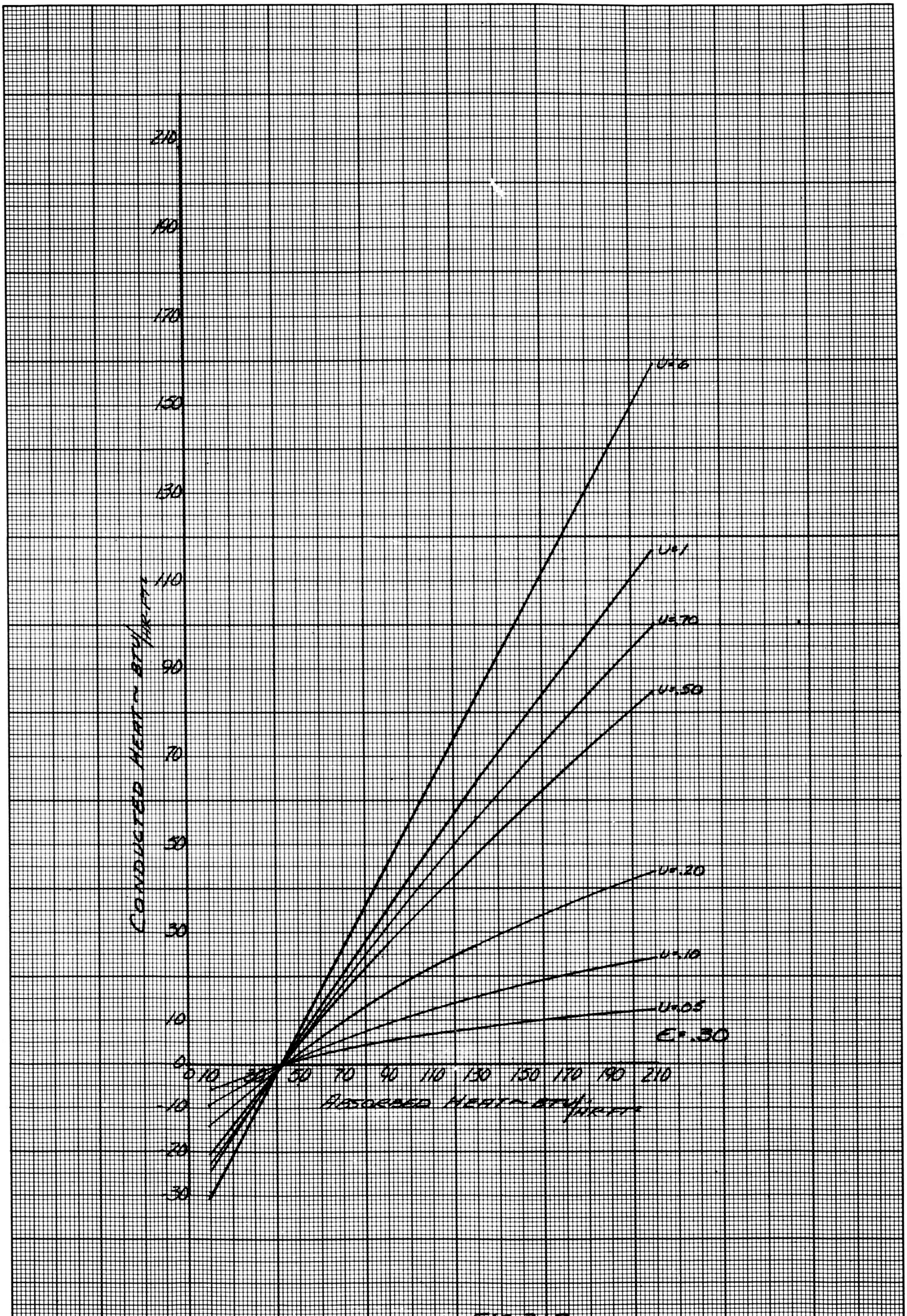

CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
U=6
U=1
U=.70
U=.50
U=.20
U=.10
U=.05
E=.30
210
190
170
150
130
110
90
70
50
30
10
0
-10
-20
-30
0 10 30 50 70 90 110 130 150 170 190 210

FIG 21A

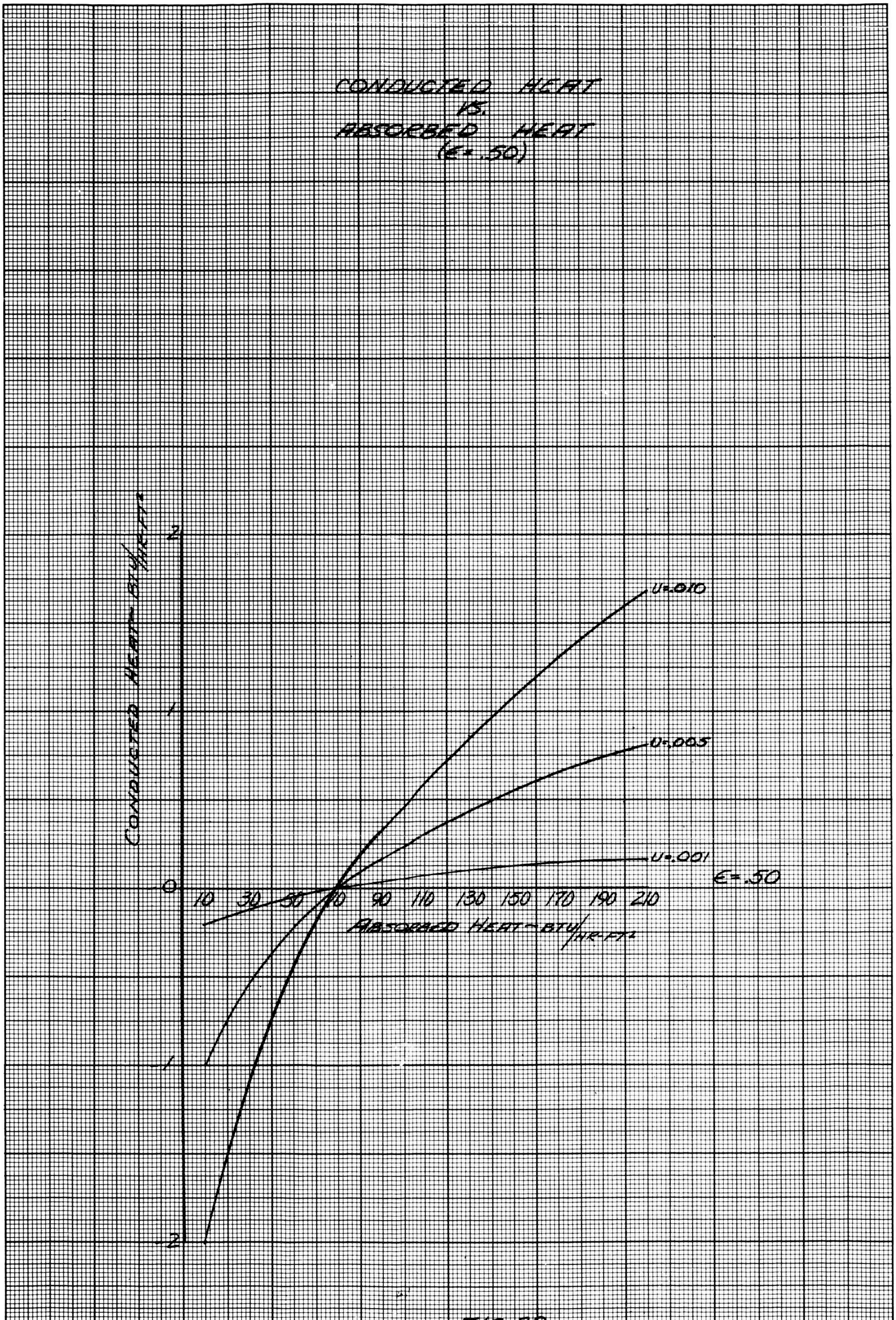

CONDUCTED HEAT
VS.
ABSORBED HEAT
(ε = .50)
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
2
1
0
-1
-2
10
30
50
70
90
110
130
150
170
190
210
U=.010
U=.005
U=.001
ε=.50

FIG 2.2

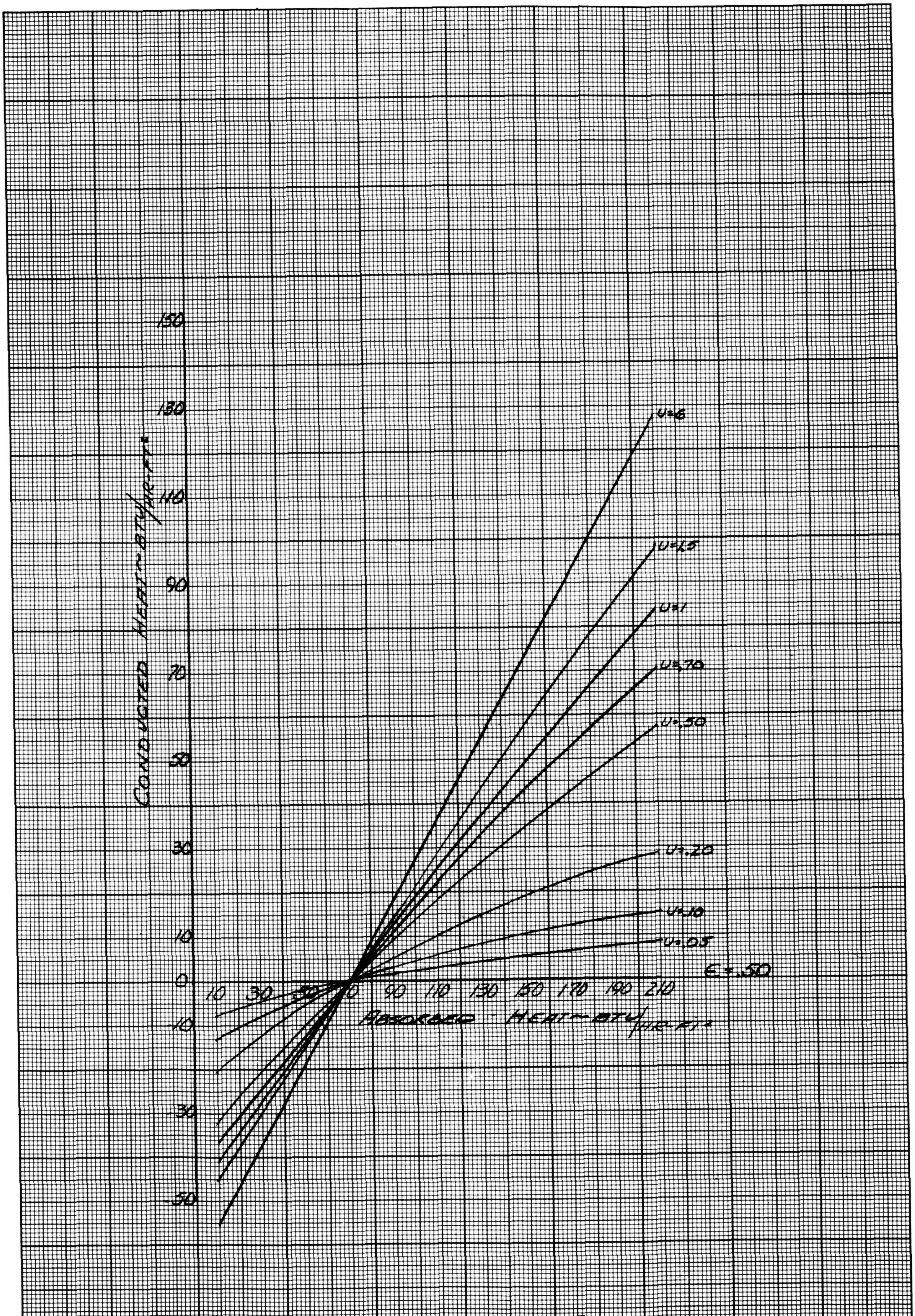

CONDUCTED HEAT ~ BTU/HR-FT²
150
130
110
90
70
50
30
10
0
-10
-30
-50
U=6
U=2.5
U=1
U=.70
U=.50
U=.20
U=.10
U=.05
E=.50
10
30
50
70
90
110
130
150
170
190
210
ABSORBED HEAT ~ BTU/HR-FT²

FIG 22A

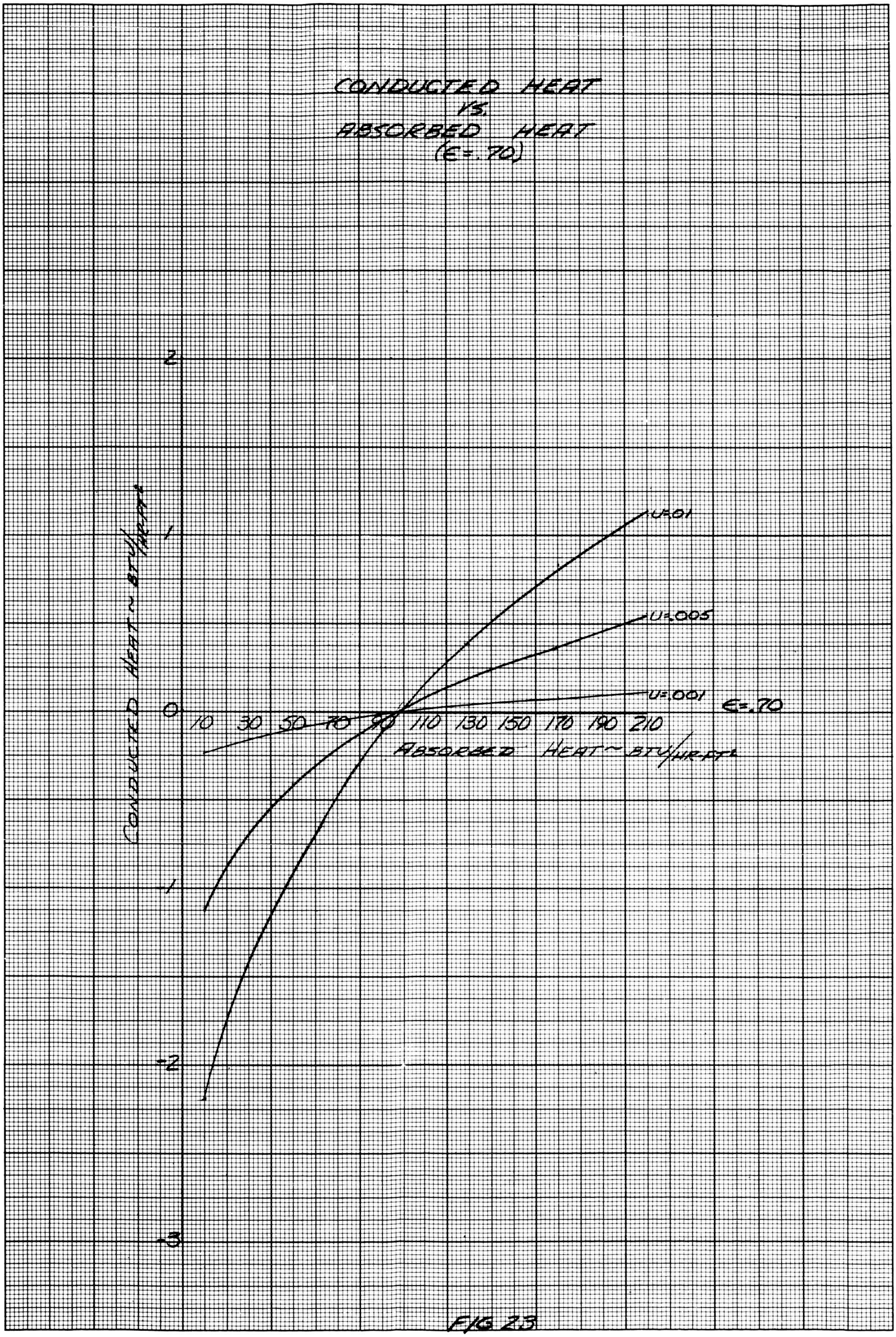

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E=.70)
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
2
1
0
-1
-2
-3
10
30
50
70
90
110
130
150
170
190
210
U=.01
U=.005
U=.001
E=.70

FIG 23

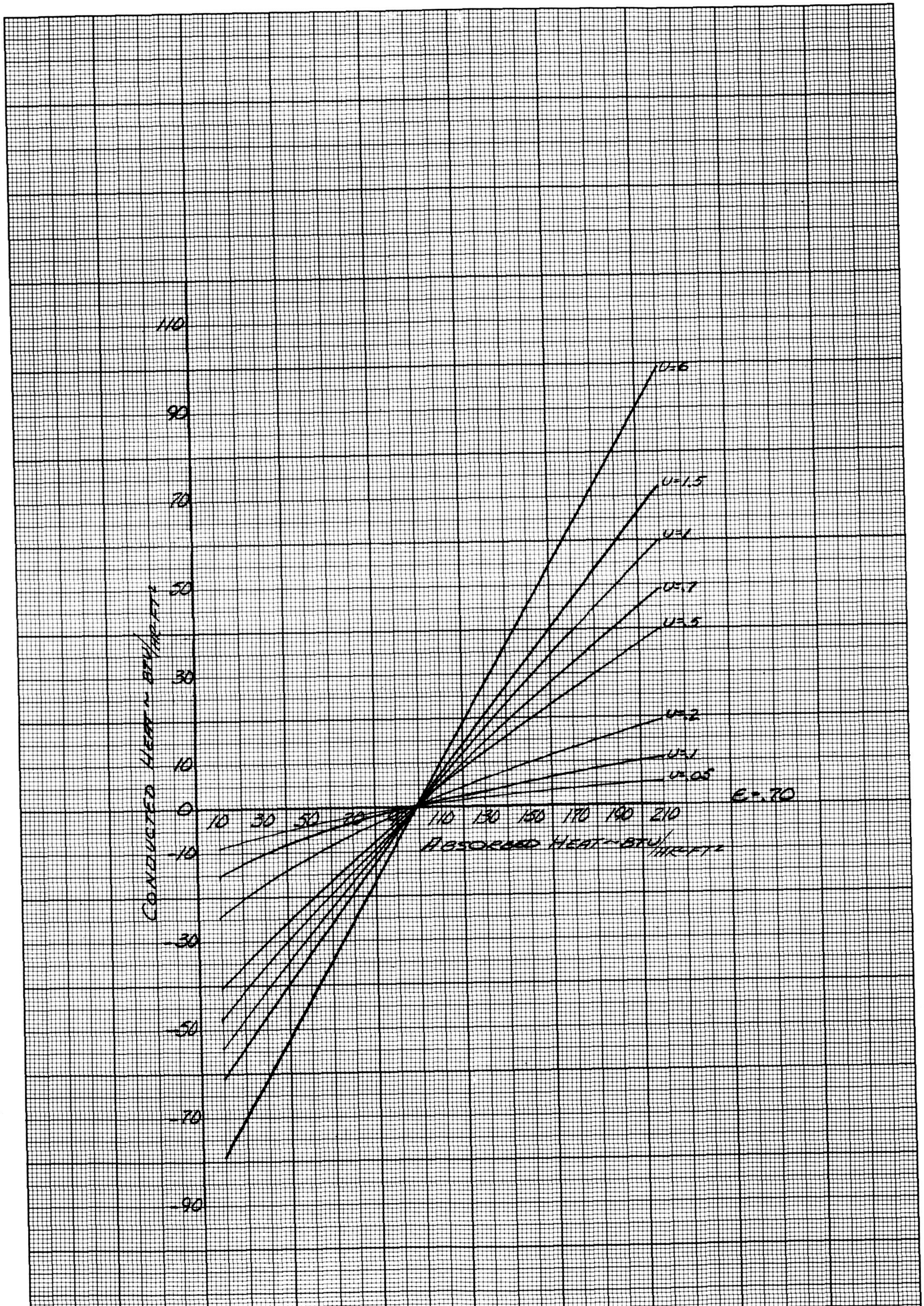

110
90
70
50
30
10
0
-10
-30
-50
-70
-90
CONDUCTED HEAT ~ BTU/HR-FT²
10 30 50 70 90 110 130 150 170 190 210
ABSORBED HEAT ~ BTU/HR-FT²
U=6
U=1.5
U=1
U=.7
U=.5
U=.2
U=.1
U=.05
E=.70

FIG 23A

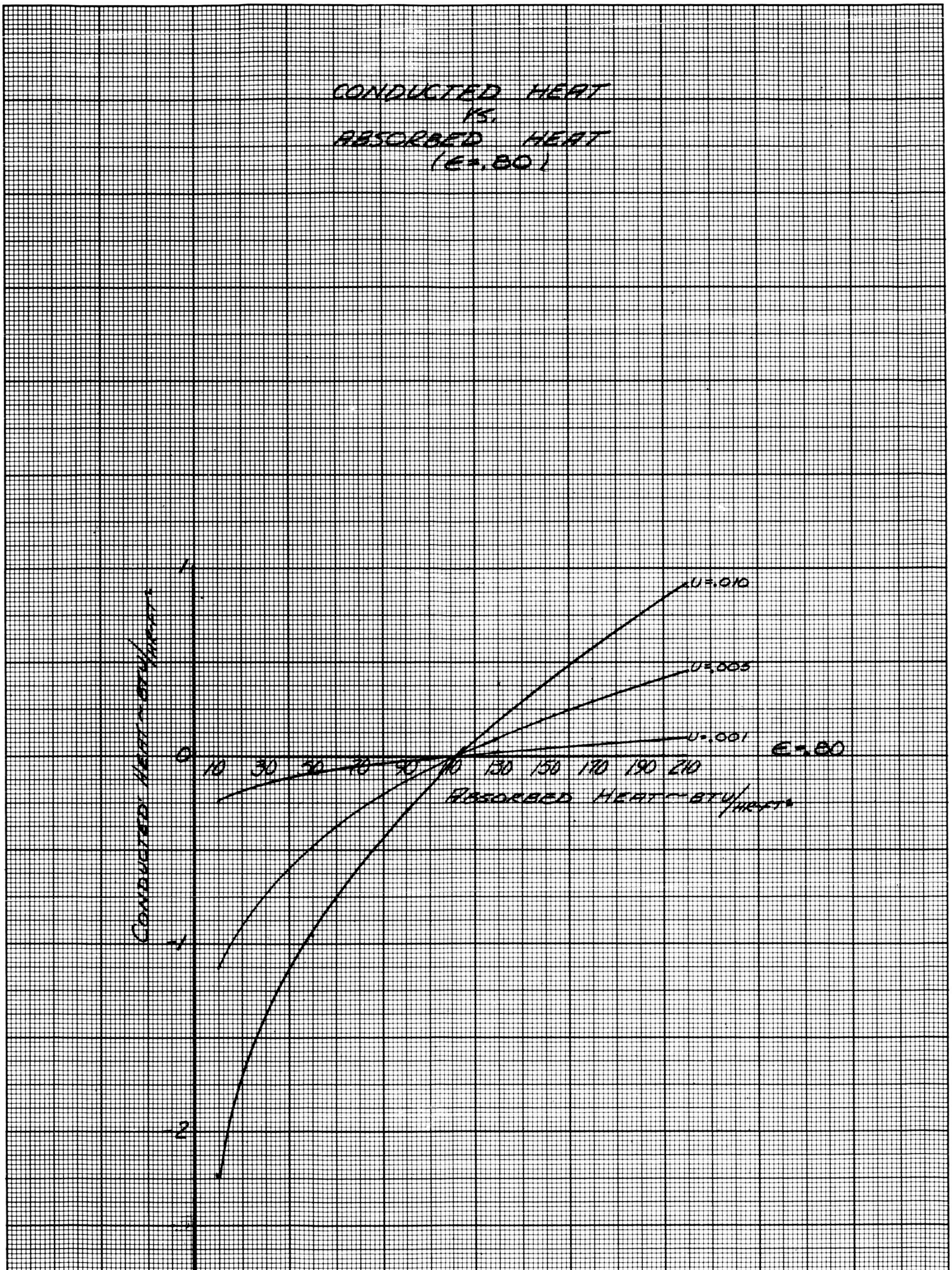

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E=.80)
U=.010
U=.005
U=.001
E=.80
CONDUCTED HEAT ~ BTU/HR FT²
ABSORBED HEAT ~ BTU/HR FT²
1
0
-1
-2
-3
10
30
50
70
90
110
130
150
170
190
210

FIG 24

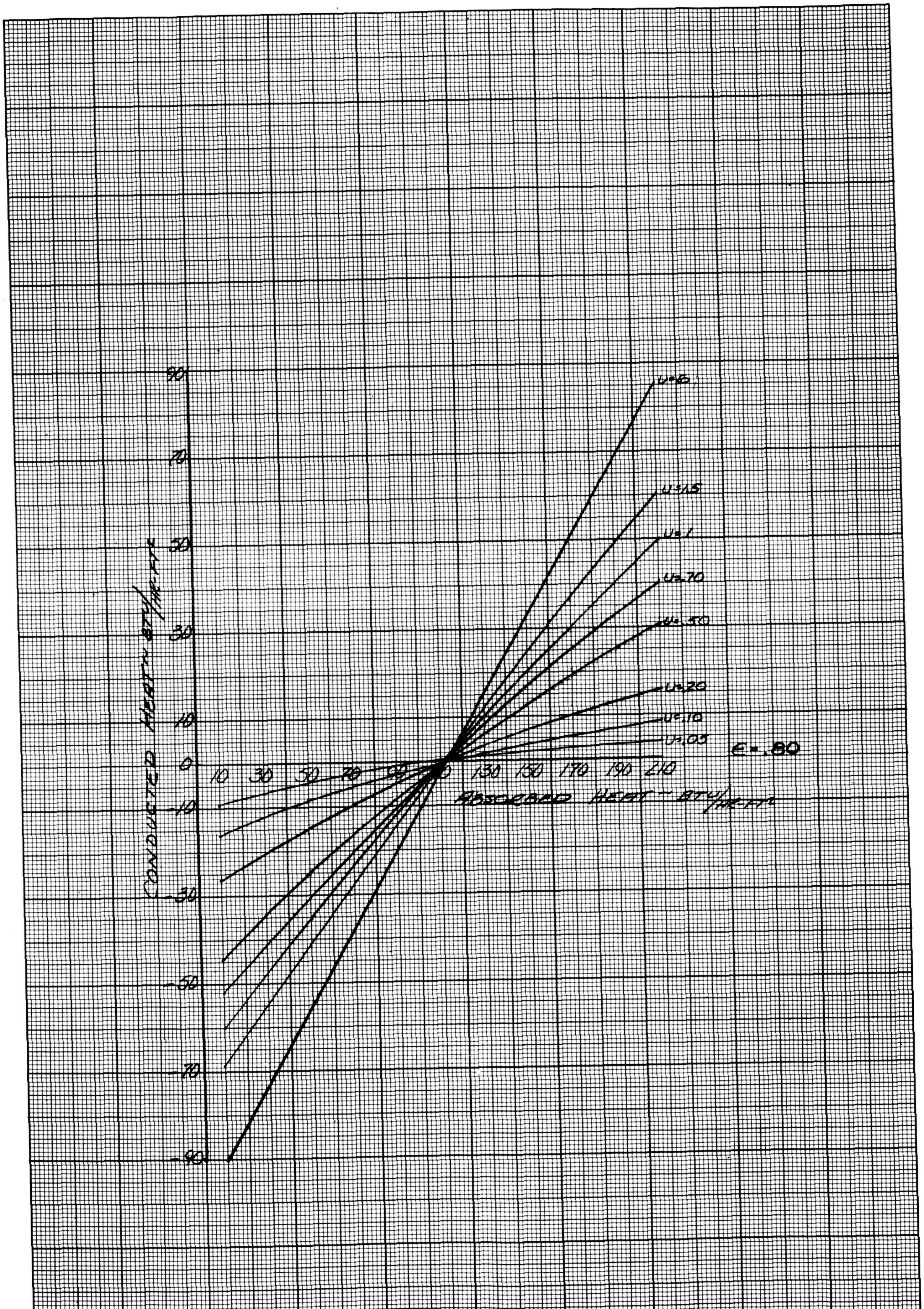

CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
90
70
50
30
10
0
-10
-30
-50
-70
-90
10
30
50
70
90
130
150
170
190
210
U=6
U=1.5
U=1
U=.70
U=.50
U=.20
U=.10
U=.05
E=.80

FIG 24A

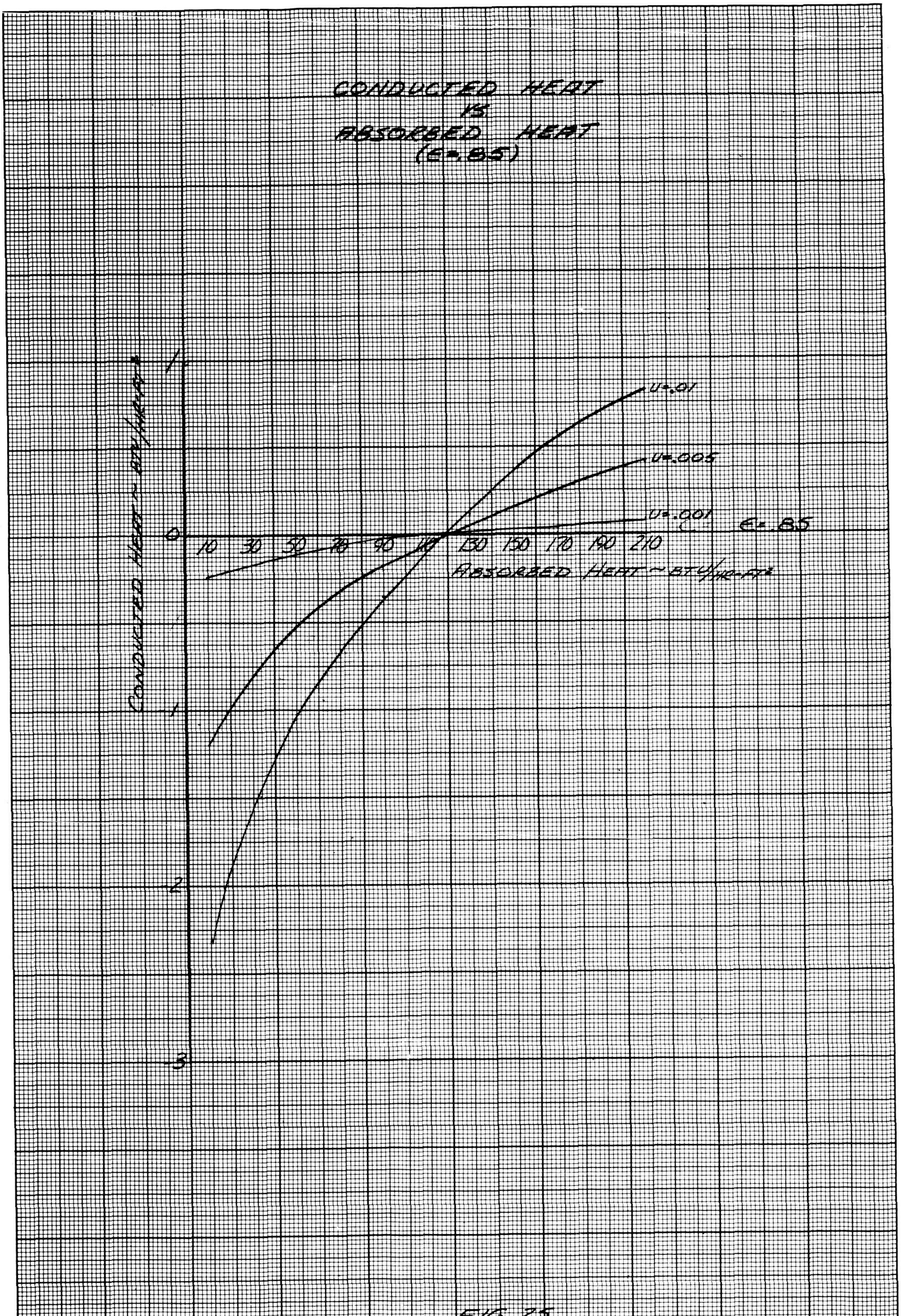

CONDUCTED HEAT
VS
ABSORBED HEAT
(E=.85)
U=.01
U=.005
U=.001
E=.85
1
0
-1
-2
-3
10 30 50 70 90 110 130 150 170 190 210
ABSORBED HEAT ~ BTU/HR-FT²
CONDUCTED HEAT ~ BTU/HR-FT²

FIG 25

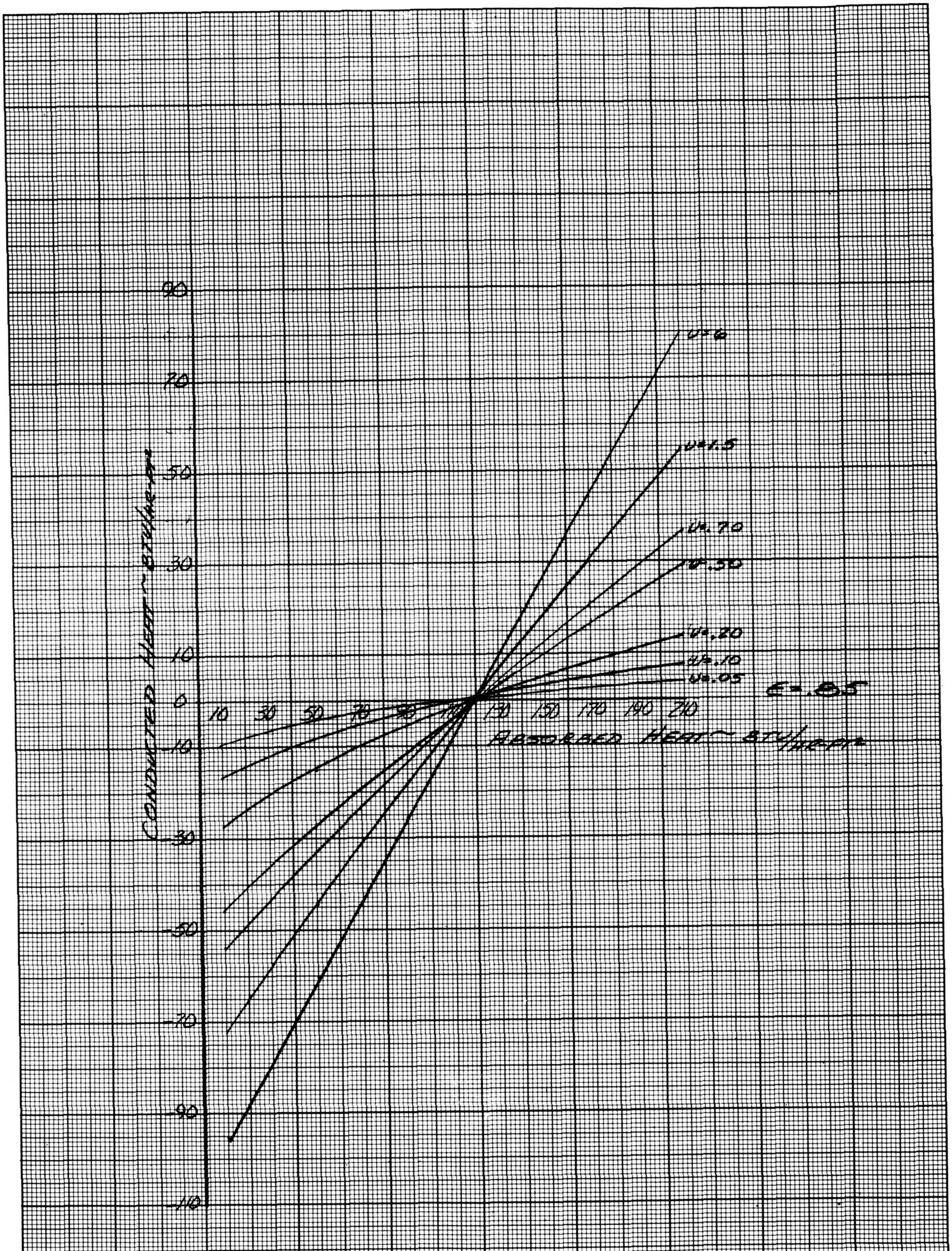

90
70
50
30
10
0
-10
-30
-50
-70
-90
-110
10 30 50 70 90 110 130 150 170 190 210
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
U=6
U=1.5
U=.70
U=.50
U=.20
U=.10
U=.05
E=.85

FIG 25A

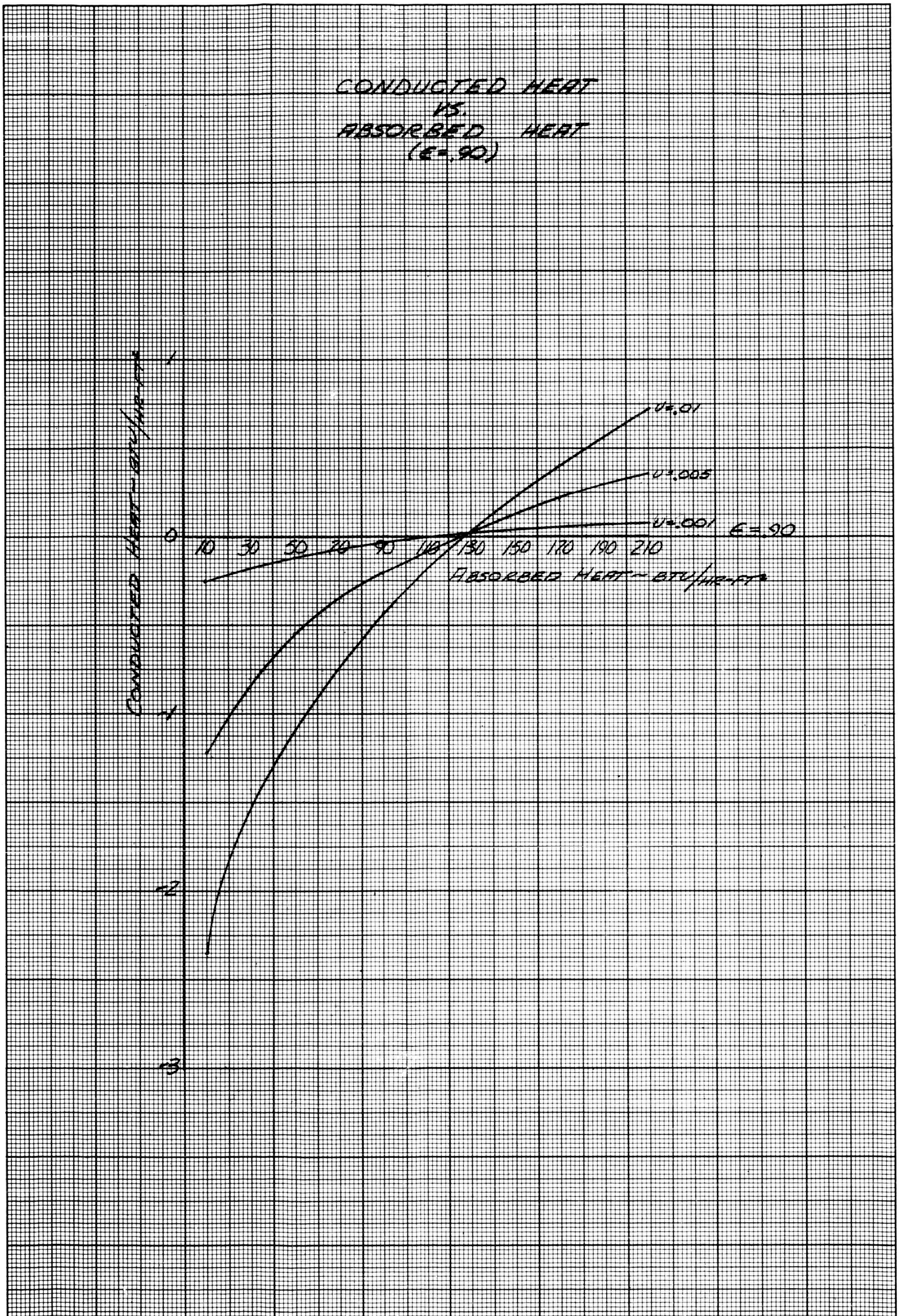

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E=.90)
CONDUCTED HEAT~BTU/HR-FT²
ABSORBED HEAT~BTU/HR-FT²
U=.01
U=.005
U=.001
E=.90
1
0
-1
-2
-3
10
30
50
70
90
110
130
150
170
190
210

FIG 26

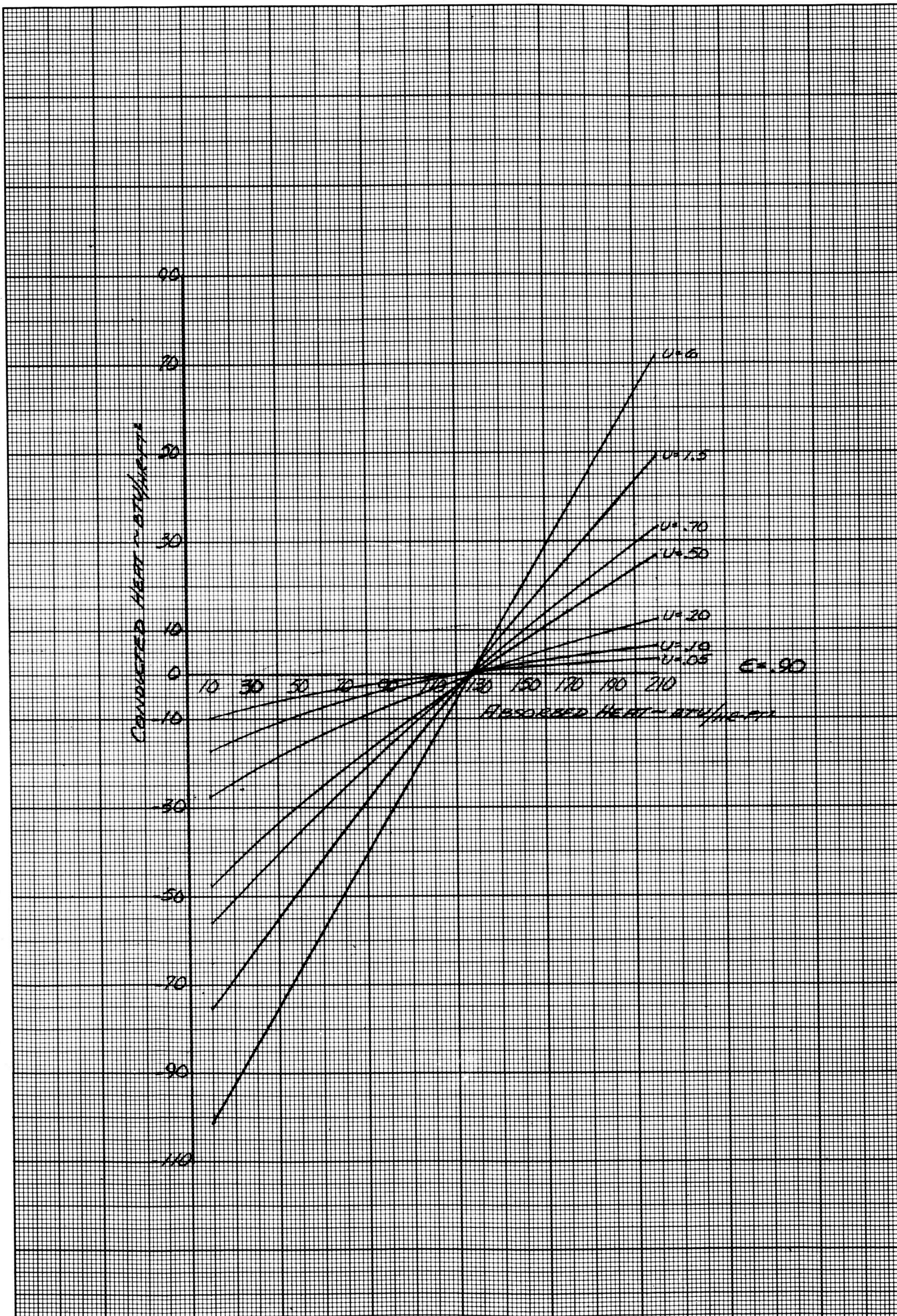

90
70
50
30
10
0
-10
-30
-50
-70
-90
-110
10 30 50 70 90 110 130 150 170 190 210
CONDUCTED HEAT ~ BTU/HR-FT²
ABSORBED HEAT ~ BTU/HR-FT²
U=6
U=1.5
U=.70
U=.50
U=.20
U=.10
U=.05
E=.90

FIG. 26A

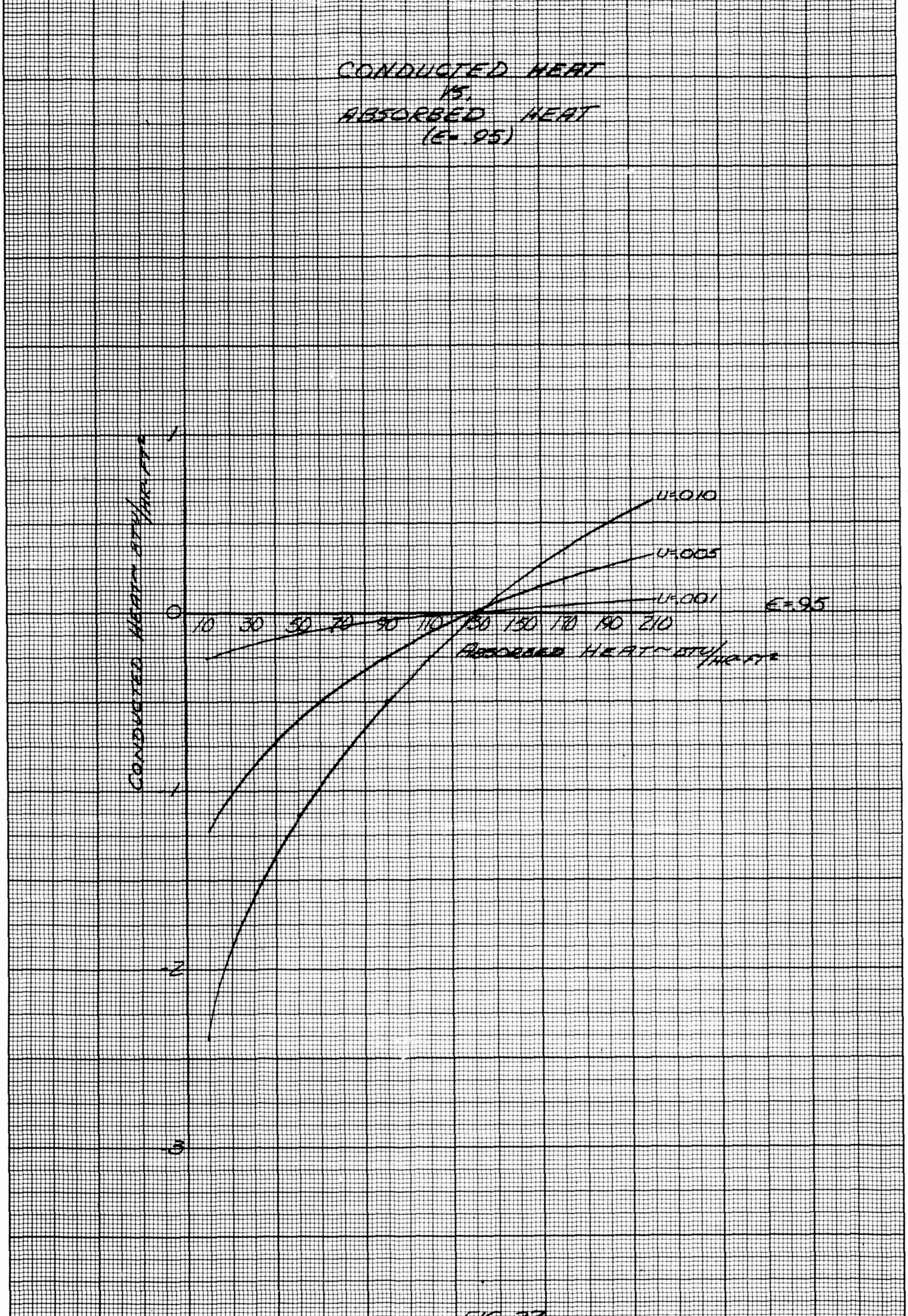

CONDUCTED HEAT
VS.
ABSORBED HEAT
(E=.95)
CONDUCTED HEAT~BTU/HR FT²
ABSORBED HEAT~BTU/HR FT²
1
0
-1
-2
-3
10 30 50 70 90 110 130 150 170 190 210
U=.010
U=.005
U=.001
E=.95

FIG 27

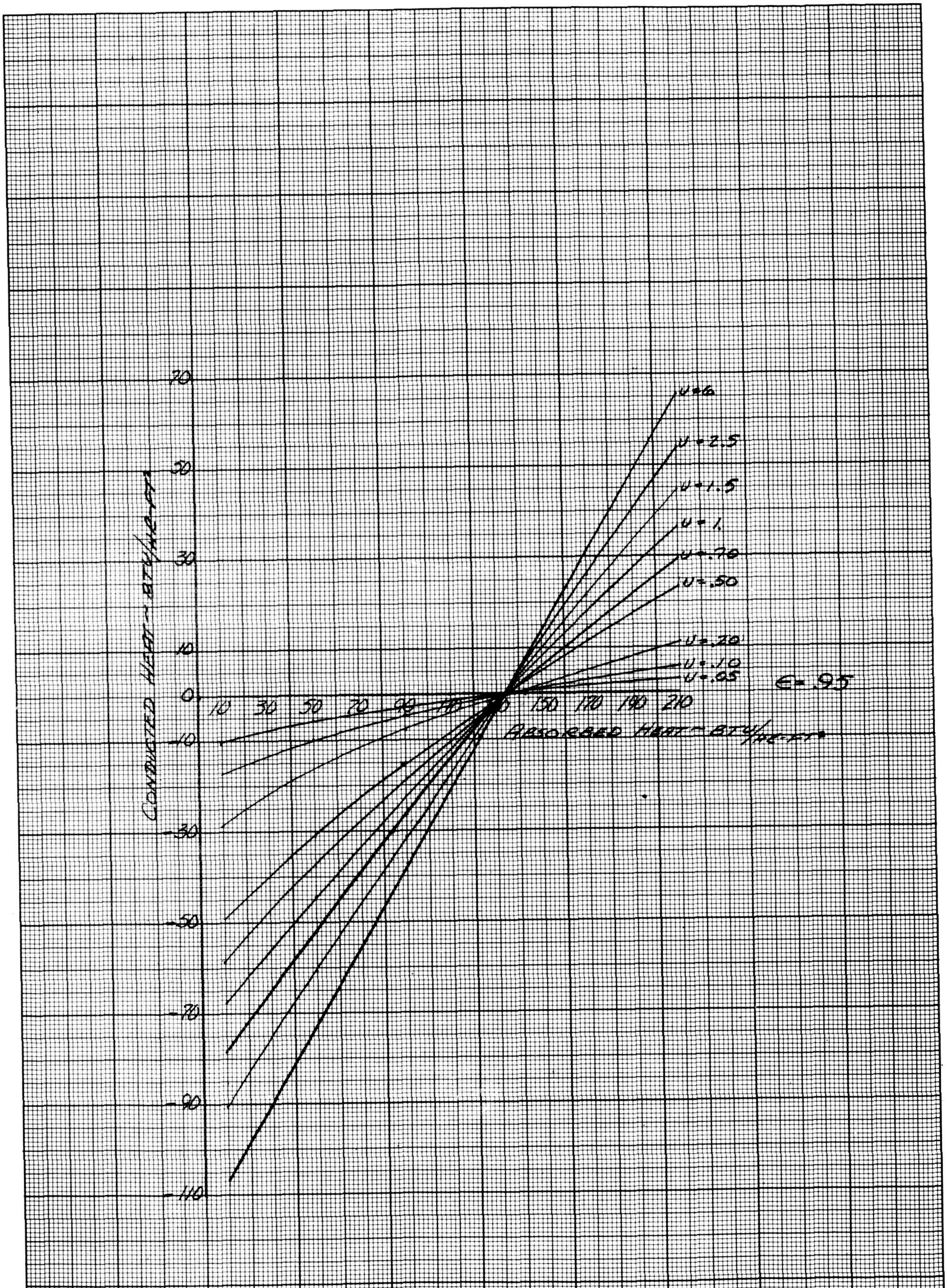

70
50
30
10
0
-10
-30
-50
-70
-90
-110
CONDUCTED HEAT ~ BTU/HR-FT²
U=6
U=2.5
U=1.5
U=1.
U=.70
U=.50
U=.20
U=.10
U=.05
ε=.95
10 30 50 70 90 110 130 150 170 190 210
ABSORBED HEAT ~ BTU/HR-FT²

FIG 27 A

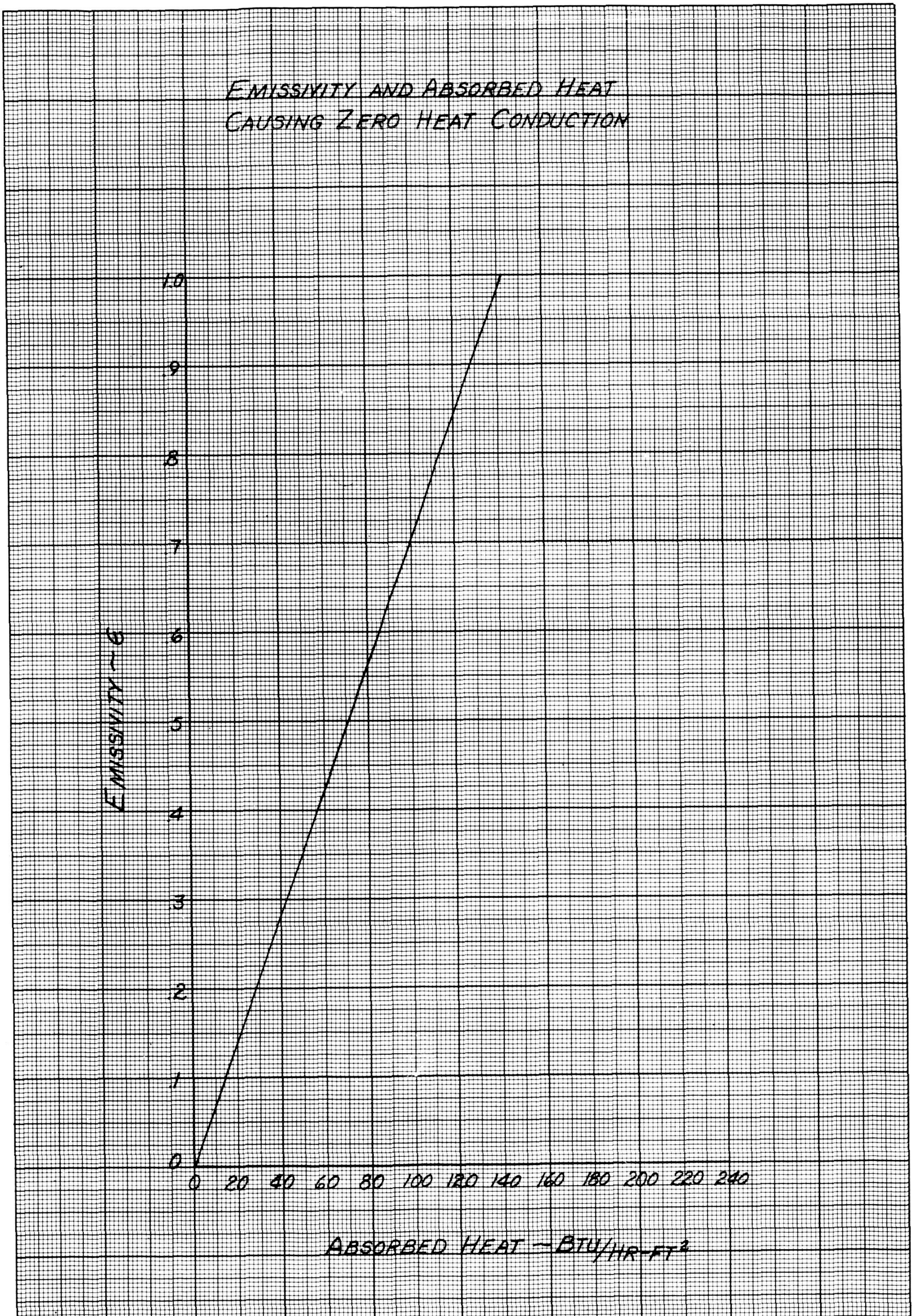
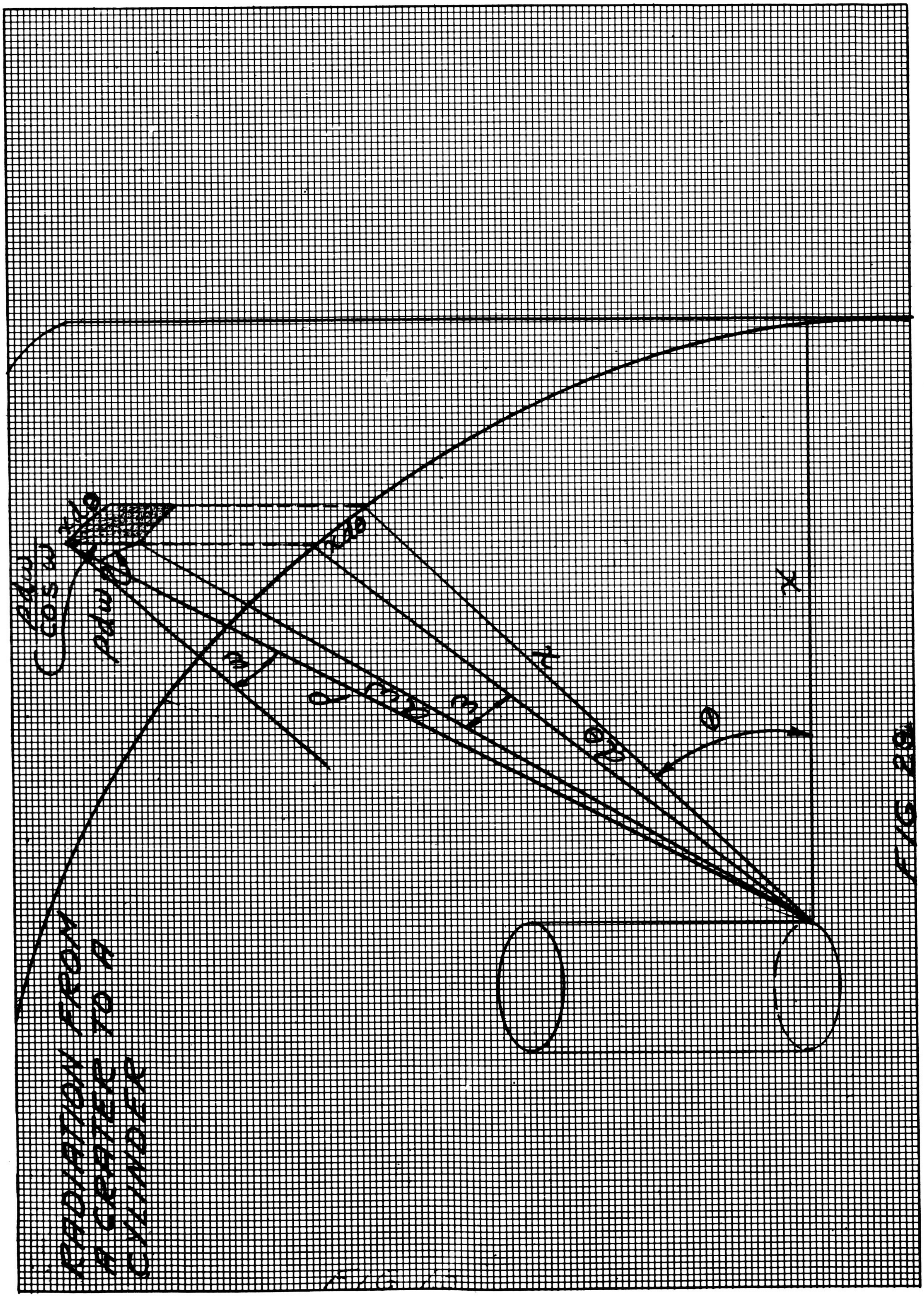

EMISSIVITY AND ABSORBED HEAT
CAUSING ZERO HEAT CONDUCTION
EMISSIVITY ~ ε
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0 20 40 60 80 100 120 140 160 180 200 220 240
ABSORBED HEAT ~ BTU/HR-FT²

FIG. 28



RADIATION FROM A CRATER TO A CYLINDER

FIG. 29

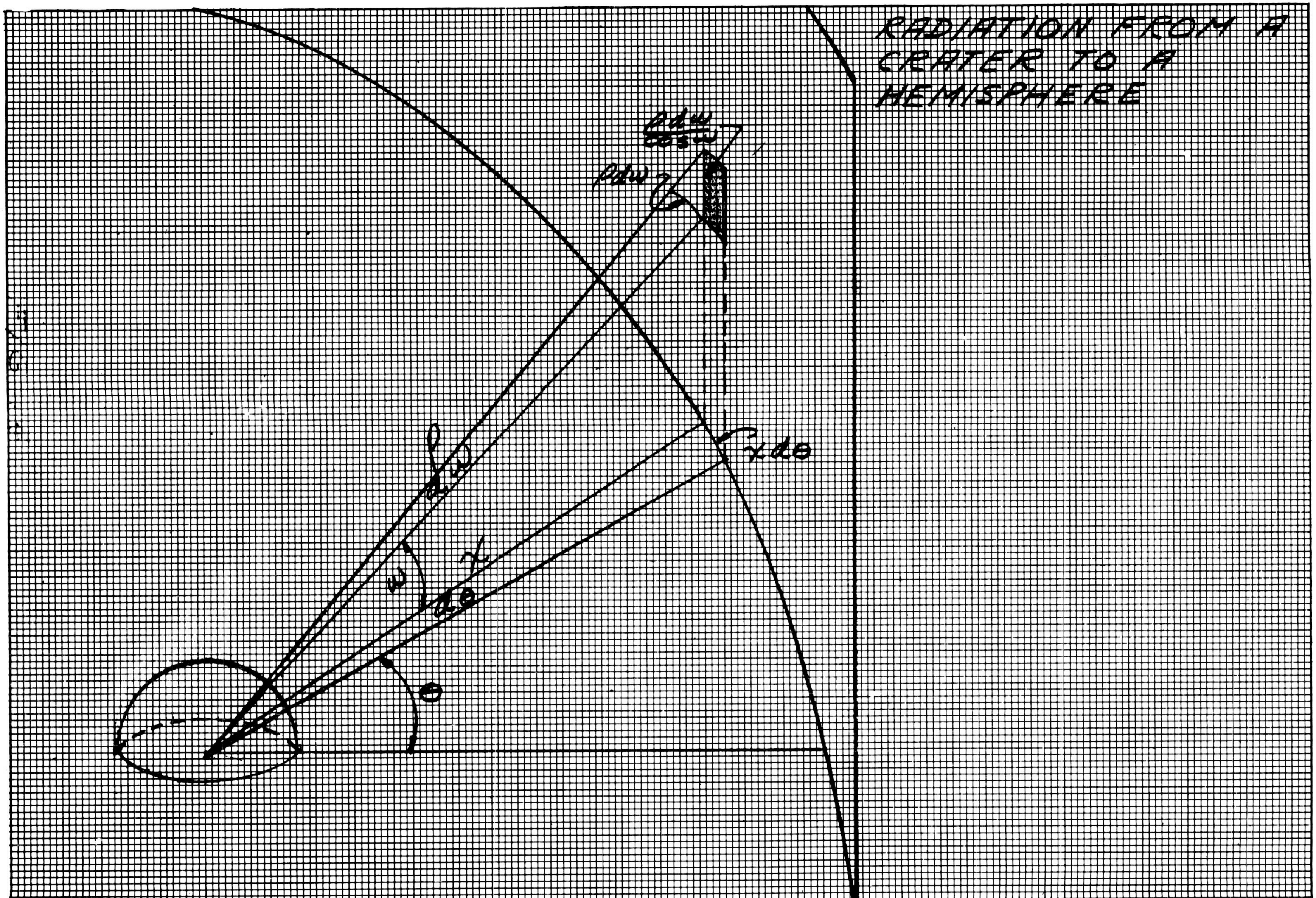

RADIATION FROM A
CRATER TO A
HEMISPHERE
ρdω/cos ω
ρdω
ρ
dω
ω
x
dθ
θ
xdθ

FIG 30

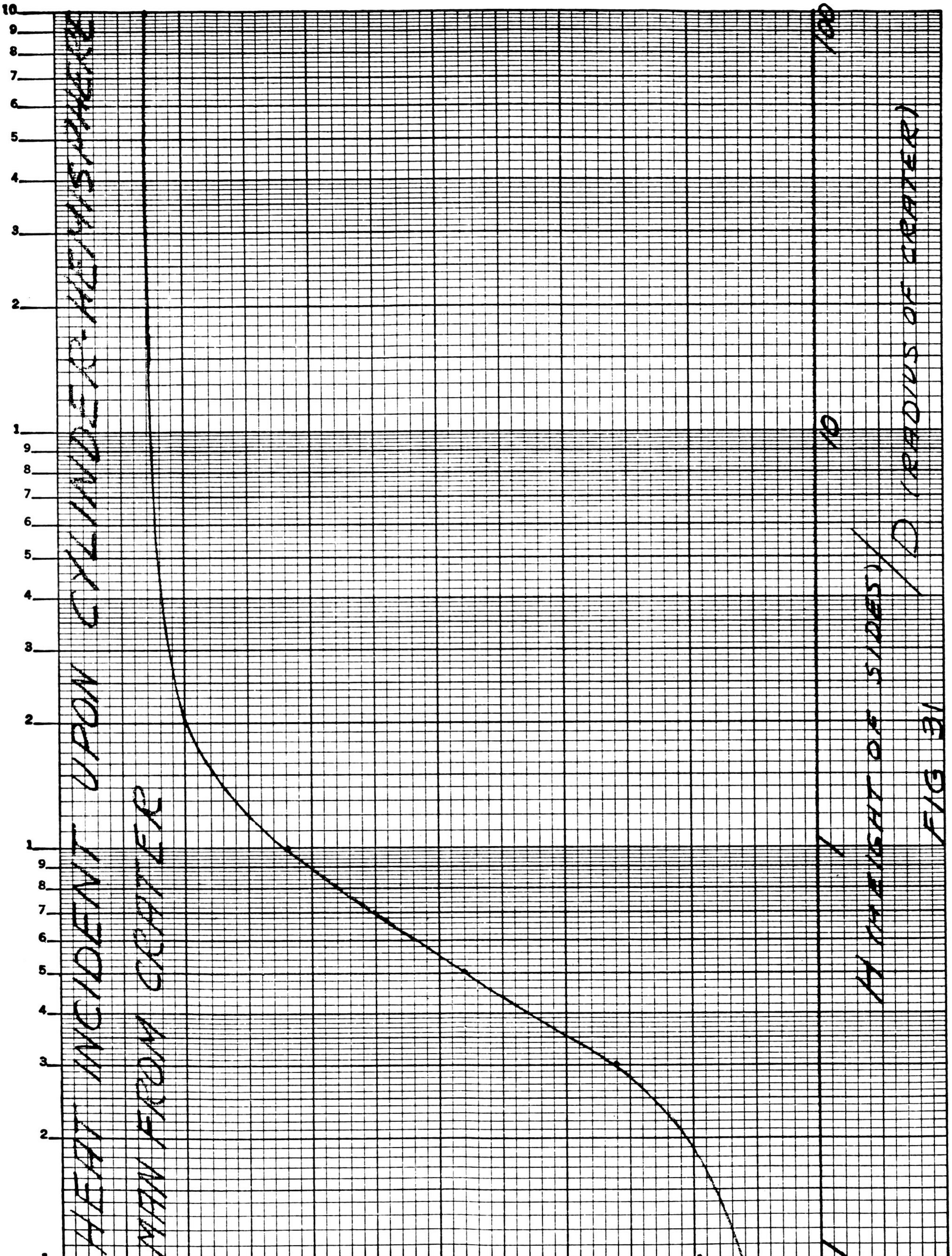

HEAT INCIDENT UPON CYLINDER-HEMISPHERE
MAN FROM CRATER
H (HEIGHT OF SIDES) / D (RADIUS OF CRATER)
q/A FOR ENTIRE BODY, BTU/HR-FT²
.60
.50
.40
.30
.20
.10
0
1
10
100

FIG 31

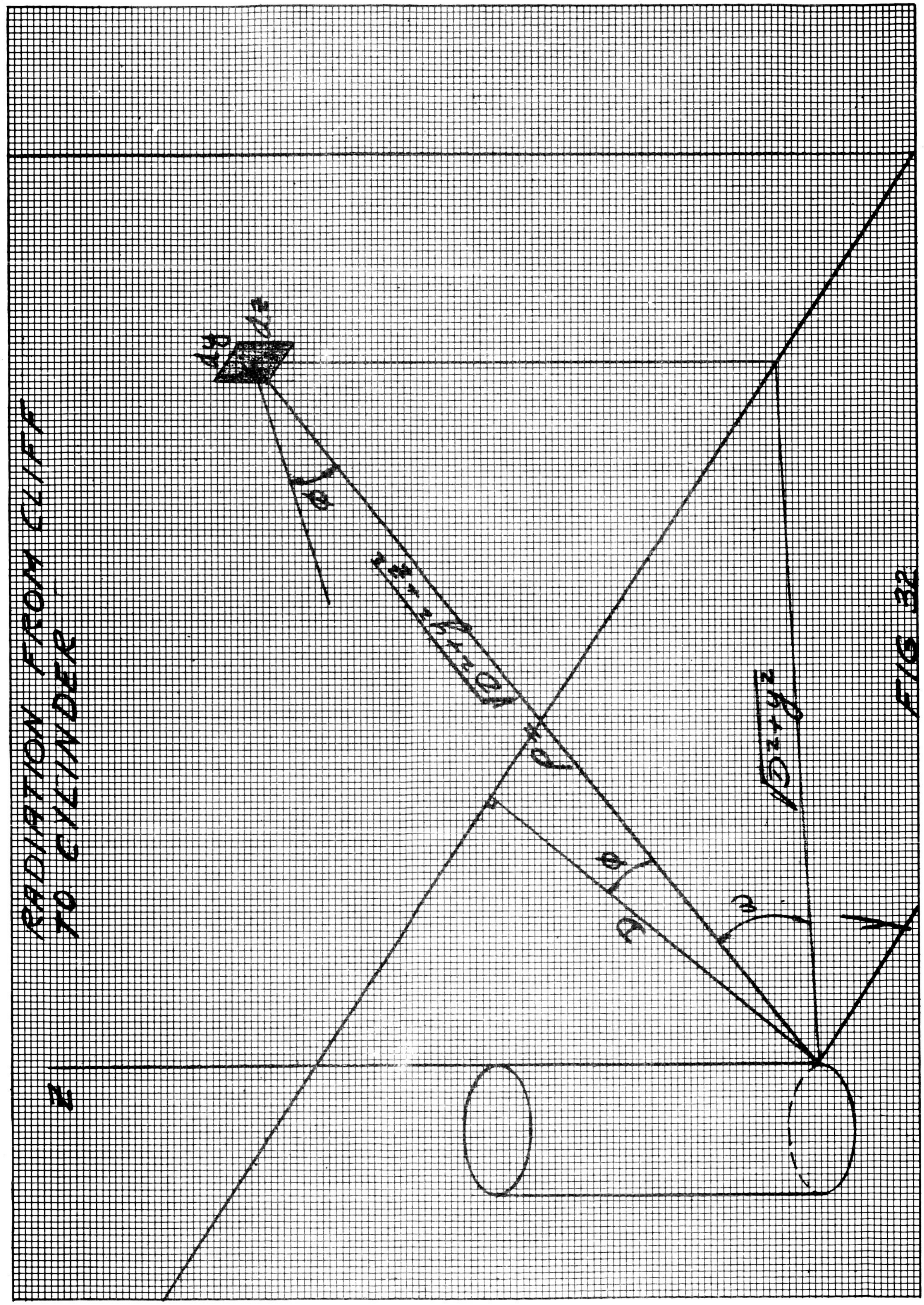


FIG 32

RADIATION FROM CLIFF TO HEMISPHERE

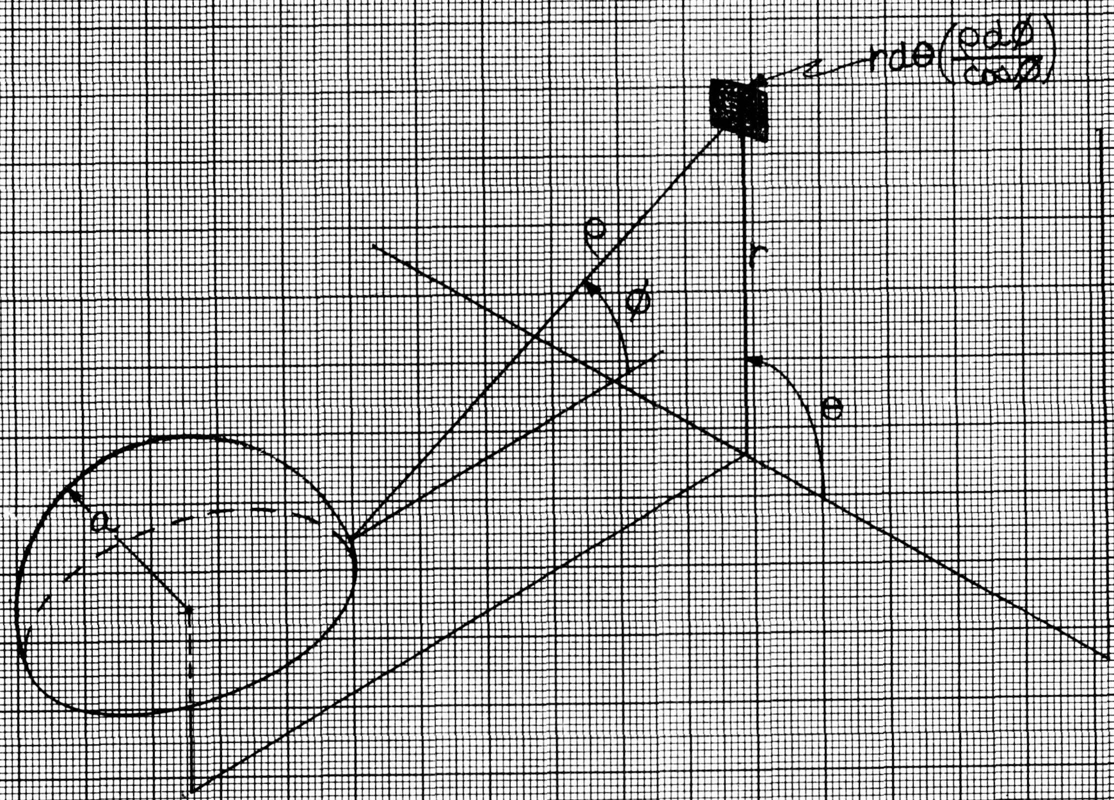


FIGURE - 33

7.0 APPENDIXES

APPENDIX A

This appendix explains the methods of finding the projected areas of the elliptic cylinder used to represent the torso and the tangent cylinders used to represent the legs. Since, in each instance, these projected areas are taken to be rectangles, of height $H \sin \phi$, the problem is reduced to that of finding the projection of the exposed circumference normal to the direction of sight, as viewed with parallel rays.

Ellipse

Figure A-1 illustrates the ellipse projected on the lunar plain by the torso (see fig. 5). For a "line-of-sight" angle θ, C_p represents the projected length of the perimeter. From the geometry one has

$$x = a \cos \phi \qquad x = R \cos \psi$$

$$y = b \sin \phi \qquad y = R \sin \psi$$

from which

$$\frac{dy}{dx} = - \tan \theta = - \frac{b}{a} \frac{1}{\tan \phi}$$

$$\frac{y}{x} = \frac{b}{a} \tan \phi = \tan \psi$$

$$\tan \theta = \frac{b^2}{a^2} \frac{1}{\tan \psi}$$

The desired projection C_p is

$$C_p = 2R \cos (\pi/2 - \theta - \psi)$$

$$= 2\sqrt{x^2 + y^2} \cdot \sin (\theta + \psi)$$

$$= 2a \cos \phi \sqrt{1 + \frac{b^2}{a^2} \tan^2 \phi} \ \sin (\theta + \psi)$$

Considerable algebraic and trigonometric manipulation leads to

$$C_p = 2a\sqrt{1 - \left(\frac{a^2 - b^2}{a^2}\right)\cos^2\theta}$$

Tangent Cylinders

Figure A-2 depicts the top view of the legs on the lunar plain. Radiation to cylinder X is desired. That from quadrants 1 and 2 is known, so the question here is, for a given "line-of-sight" angle θ, what is the projection, C_p, of the circumference of X as viewed from quadrant 4. The tangent lines to the two cylinders define C_p. The distances a, b, and c are shown. The following relations are evident:

$$C_p = D/2 + a$$

$$a = b \cos\theta$$

$$b = D - c$$

$$c = (D/2)/\cos\theta$$

Substitution leads to the final result:

$$C_p = D\cos\theta$$

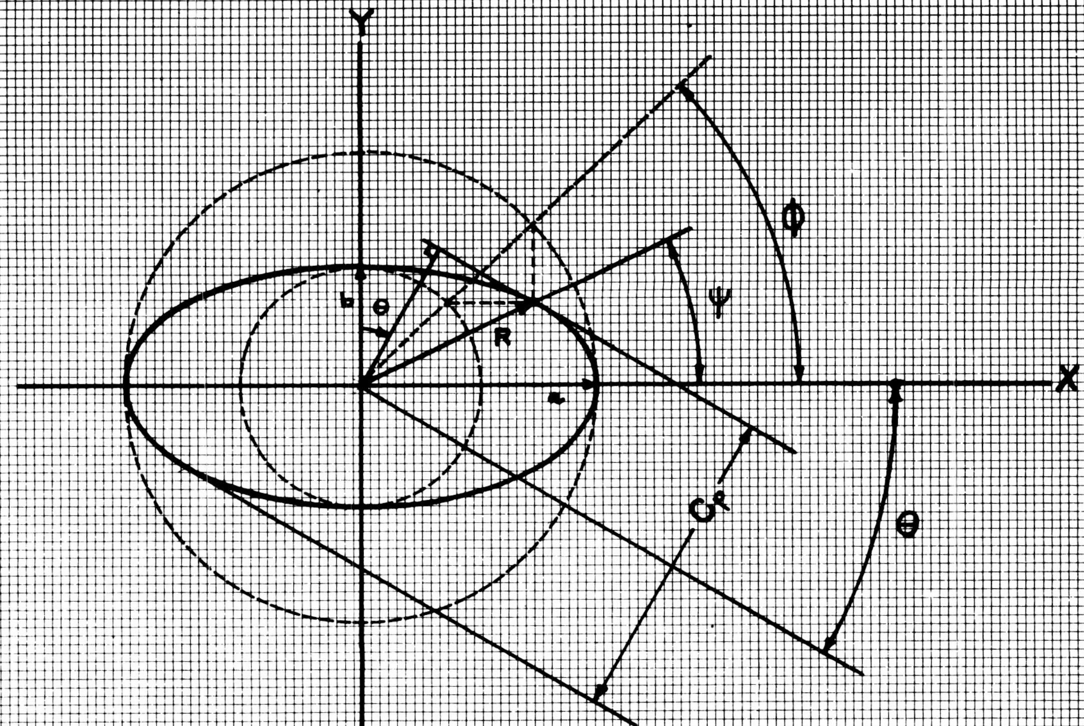


Figure A-1.- Ellipse

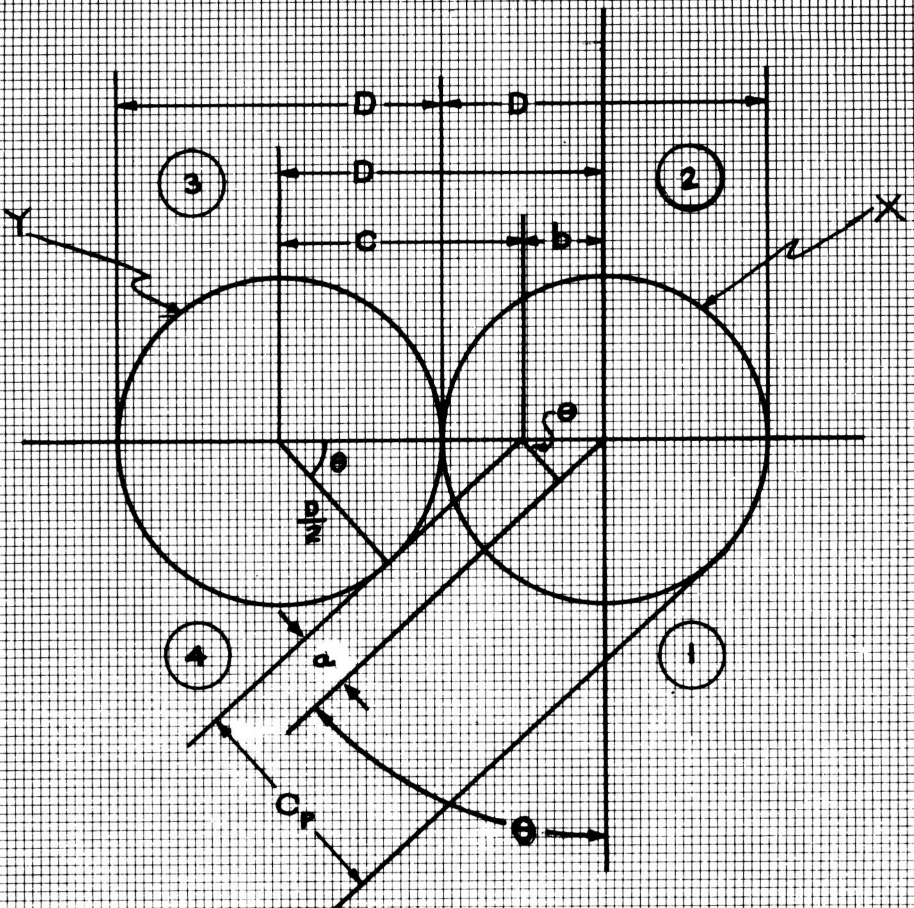


Figure A-2.- Top view of legs on the lunar plain

APPENDIX B

The determination of the projected area of a hemisphere whose base is parallel to the lunar plain was performed in the following manner. Figure B-1 shows the hemisphere viewed by parallel rays from a point on a plane. The projected area, A_p, normal to the line-of-sight is seen to be the difference between the area of a semicircle (radius = a) and a semiellipse (major radius = a, minor radius = a cos ϕ). Thus,

$$A_p = \frac{\pi a^2}{2} - \frac{1}{2}\pi a(a \cos \phi)$$

$$= \frac{\pi a^2}{2}(1 - \cos \phi)$$

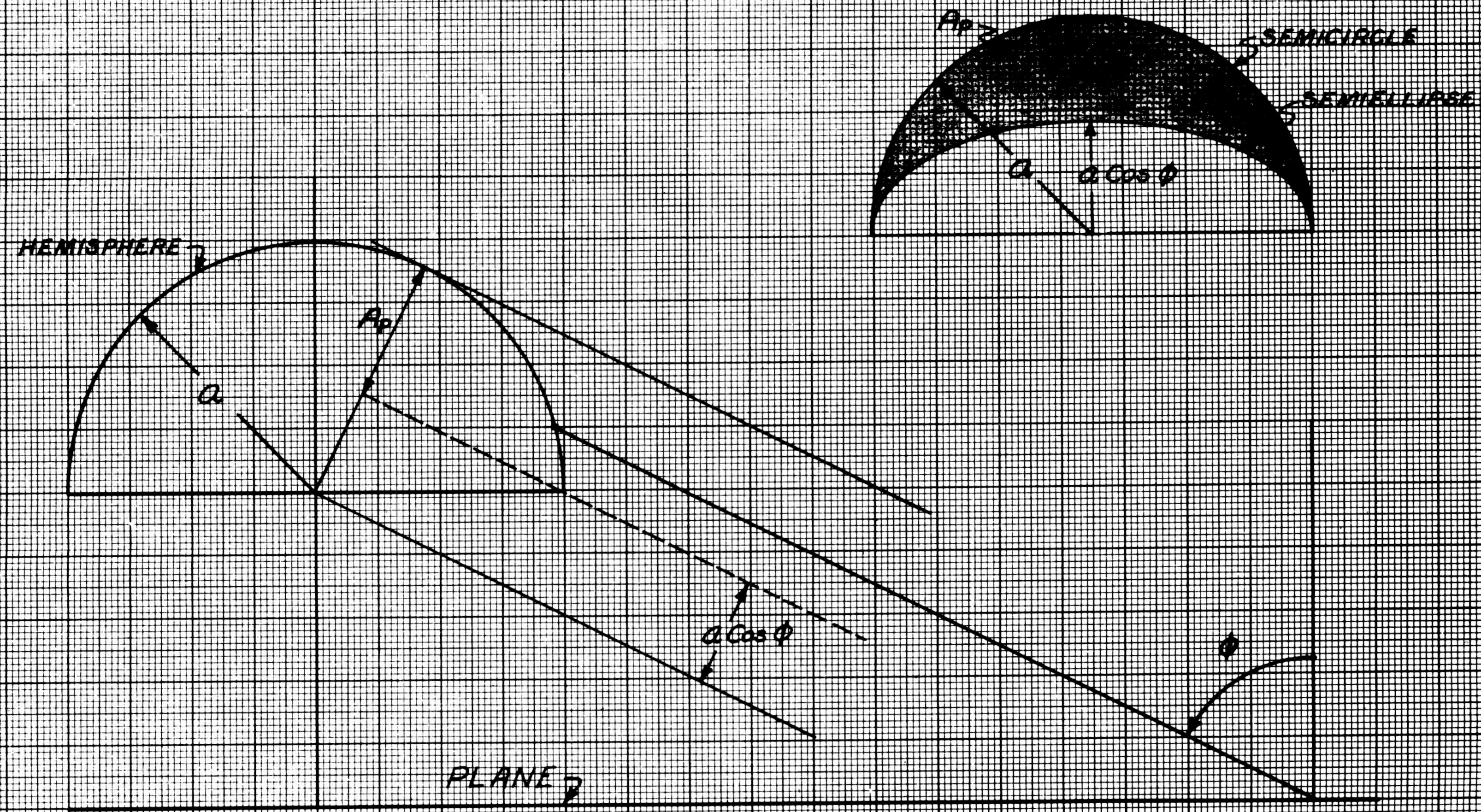
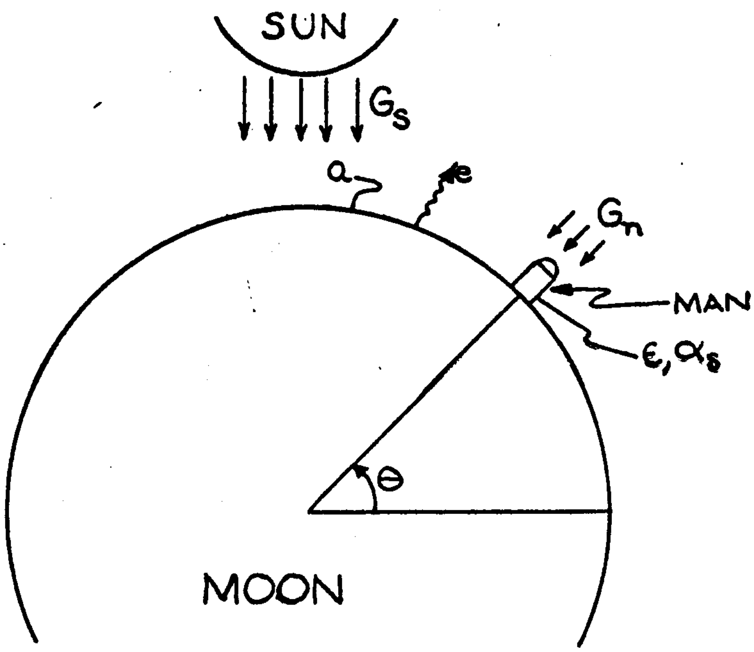


Figure B-1.- Hemisphere viewed by parallel rays from a point on a plane

APPENDIX C

The total heat per unit area absorbed by a figure on the lunar surface is derived in this appendix. The sketch below illustrates the geometrical parameters involved.



The following rotation is used:

G_s = Solar constant

G_n = Solar irradiation normal to surface

α_s = Solar absorptivity of man's surface

ε = Infrared emissivity of man's surface

a = Albedo of moon's surface

e = Emittance of moon's surface

A_t = Total exposed surface area of man

A_{p_s} = Projected area of man, normal to sun's rays

F = Fraction of moon's radiosity (emittance or reflection) which strikes man, per unit of total surface area

F_s = G_n/G_s

F_m = A_{p_s} / A_t

Q_{abs} = Total radiation absorbed by man's surface

Q_s = Radiation absorbed due to direct solar radiation

Q_{em} = Radiation absorbed due to moon's emittance

Q_{am} = Radiation absorbed due to moon's albedo

The following heat balance may be written if one neglects multiple reflections between the moon's surface and the man.

$$Q_{abs} = Q_s + Q_{em} + Q_{am}$$

By use of the above definitions,

$$Q_s = \alpha_s\left(G_s A_{p_s}\right)$$

$$Q_{em} = \epsilon\ (e\ F\ A_t)$$

$$Q_{am} = \alpha_s\left\lfloor (a\ F_s G_s)\ F\ A_t \right\rfloor$$

Assuming that equilibrium exists between the sun and the moon's surface:

$$e = G_n(1-a)$$

$$= F_s G_s (1-a)$$

Thus,

$$Q_{abs} = \alpha_s G_s A_{p_s} + \epsilon\ G_s F_s (1-a) F\ A_t + \alpha_s\ aF_s\ G_s\ F\ A_t$$

$$\frac{Q_{abs}}{A_t} = G_s \left\{ \alpha_s F_m + \left[\epsilon(1-a) + \alpha_s a \right] F F_s \right\}$$

Special cases of this latter expression may be obtained for specific assumed geometries of the man.

For the case in which one takes the man to be a hemisphere-cylinder combination, the projected area, A_{p_s}, may be taken as the sum of a rectangle and the projected area of the hemisphere. If the cylinder is of height H and diameter D, then the rectangle has an area of HD cos θ. The projected area of the hemisphere is the sum of the area of a semicircle of diameter D, $\frac{1}{2}(\pi D^2/4)$, and the area of a semi-ellipse of major diameter D and minor diameter D sin θ. This latter area is, then, $\frac{1}{2}\pi(D/2)^2 \sin\theta$. Thus,

$$A_{p_s} = HD \cos\theta + \frac{1}{8}\pi D^2 (1 + \sin\theta)$$

Since

$$A_t = \pi DH + \pi D^2/2,$$

then,

$$F_m = A_{p_s}/A_t$$

is

$$F_m = \frac{\frac{1}{\pi}\cos\theta + \frac{1}{8}\frac{D}{H}(1 + \sin\theta)}{1 + \frac{1}{2}\frac{D}{H}}$$

If the above expression for F_m and the relations for F_s in figure 9 are introduced into the above equation for Q_{abs}/A_t, then an expression for the heat absorbed by a hemisphere-cylinder man is obtained as a function of only the geometrical parameters H and D, the surface properties ε and α_s, the moon's albedo a, and the angular position θ. Figures 11 through 14 were computed by this means.

The point of maximum heat absorption may be found by examining the derivative:

$$\frac{d}{d\theta}\left(\frac{Q_{abs}}{A_t G_s}\right) = \alpha_s \frac{dF_m}{d\theta} + \left[\epsilon(1-a) + \alpha_s\, a\right] F \frac{dF_s}{d\theta}$$

For the hemisphere-cylinder the above expression for F_m may be used so that the point of maximum heat absorption is given by

$$\frac{\alpha_s}{1 + \frac{1}{2}\frac{D}{H}}\left[-\frac{1}{\pi}\sin\theta + \frac{1}{8}\frac{D}{H}\cos\theta\right] + \left[\epsilon(1-a) + \alpha_s\, a\right] F \frac{dF_s}{d\theta} = 0$$

Treating the two ranges of F_s separately, then one has:

$$28.26° \leq \theta \leq 90° \quad : \quad F_s = \sin\theta$$

$$0° \leq \theta \leq 28.26° \quad : \quad F_s = 0.039 + 0.8808\,\theta$$

Thus, the maximum heat absorption position is given by:

$28.26° \leq \theta \leq 90°$:

$$\theta_{Q_{max}} = \tan^{-1}\left\{\pi\left[\frac{1}{8}\frac{D}{H} + F\left(1 + \frac{1}{2}\frac{D}{H}\right)\left[\frac{\epsilon}{\alpha_s}(1-a) + a\right]\right]\right\}$$

$0° \leq \theta \leq 28.26°$:

$\theta_{Q_{max}}$ is the root of:

$$\frac{1}{\pi}\sin\theta_{Q_{max}} - \frac{1}{8}\frac{D}{H}\cos\theta_{Q_{max}} = F\left(1 + \frac{1}{2}\frac{D}{H}\right)\left[\frac{\epsilon}{\alpha_s}(1-a) + a\right] 0.8808.$$

These latter expressions were used with $\frac{D}{H} = 1.52/5.0$ and $a = 0.07$ to obtain figures 15 and 16.

8.0 ADDENDUM

ADDENDUM

LUNAR NIGHT

The effect of the thermally radiant environs on a man is almost totally independent of his position on the darkened portion of the lunar surface. This is due to the rapidity at which the moon dissipates its surface heat after sunset and the long night period (14 Earth days). The emission rate of the darkened lunar surface was assumed to be constant and equal to 2.63 Btu/hr-ft^2. (See reference 1.) It should be noted that since the absorbed thermal influx is independent of the solar absorptivity of the suit, the α_s has been eliminated as an investigative parameter.

The analytical technique utilized in this analyzation is identical to that developed for the illuminated portion of the moon. The heat absorbed (Btu/hr-ft^2) by the hemisphere-cylinder man is graphed, for the range of emissivities previously considered, on figure 1. Figures 2 through 8 graph conducted heats as a function of absorbed heats for a wide range of overall heat transfer coefficients. The utility of this set of figures is realized through correlation with figure 1 as demon strated in the following example.

The heat conducted through the insulation of a space-suited man during lunar night is sought. His suit properties are $\varepsilon = .5$ and $U = .050$; he is standing at a position 290° from the dawn point. From figure 1, it is seen that he absorbs .610 Btu/hr-ft^2; which when used with figure 5A gives a conducted heat of -10 Btu/hr-ft^2.

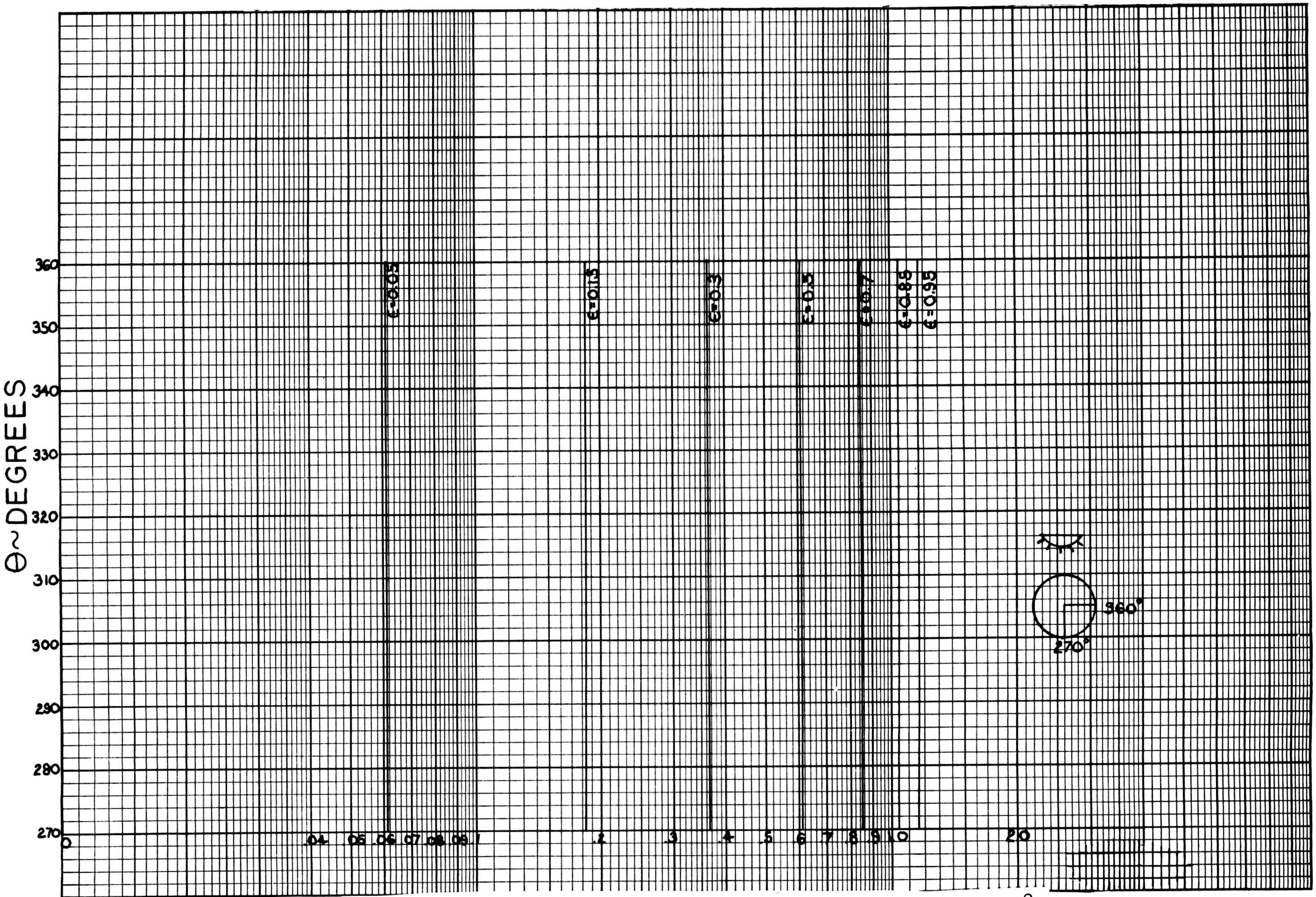


Figure 1.- Total heat absorbed/unit surface area ~ btu/hr-ft^2

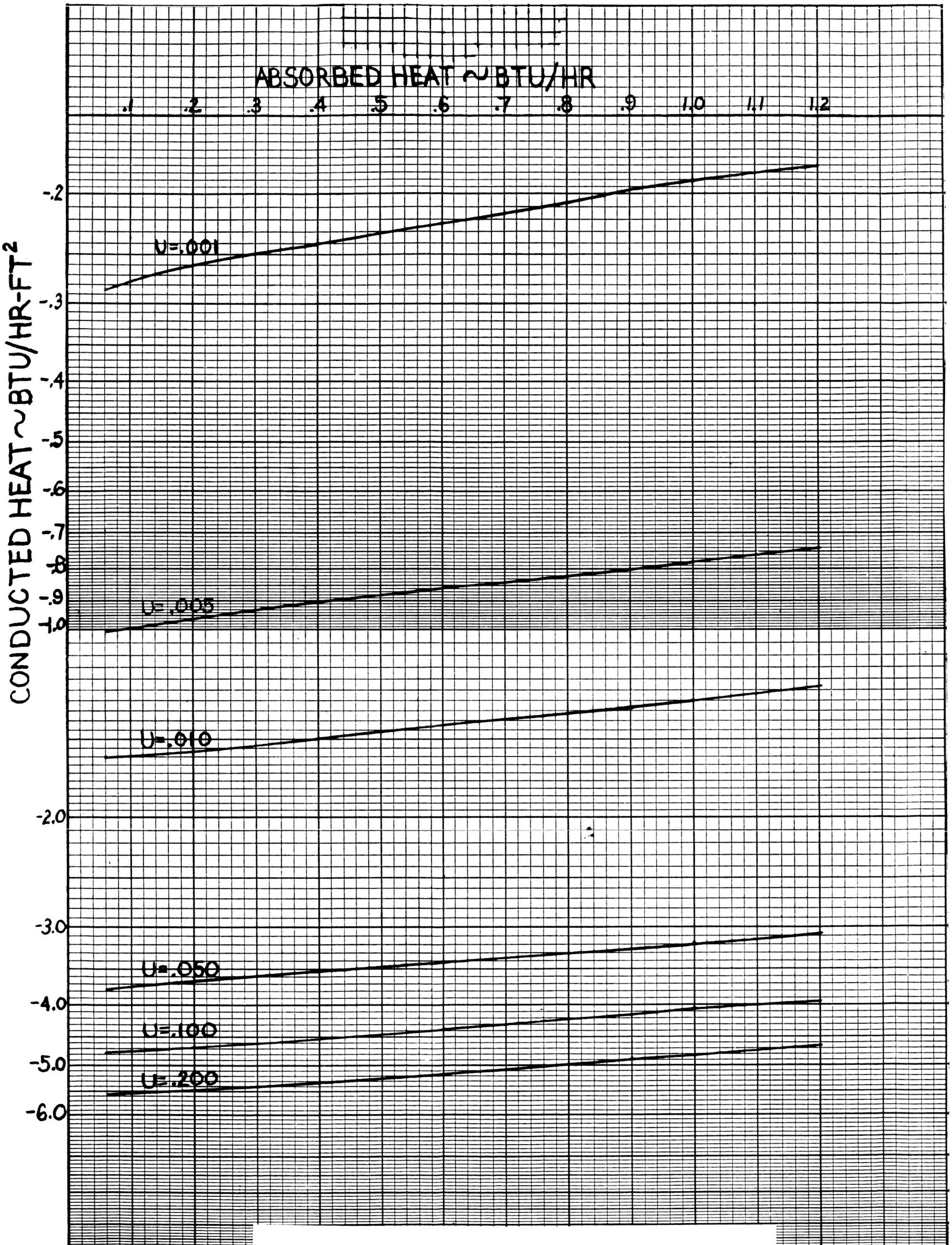


Figure 2.- Conducted heat vs. absorbed heat

$\epsilon = .05$

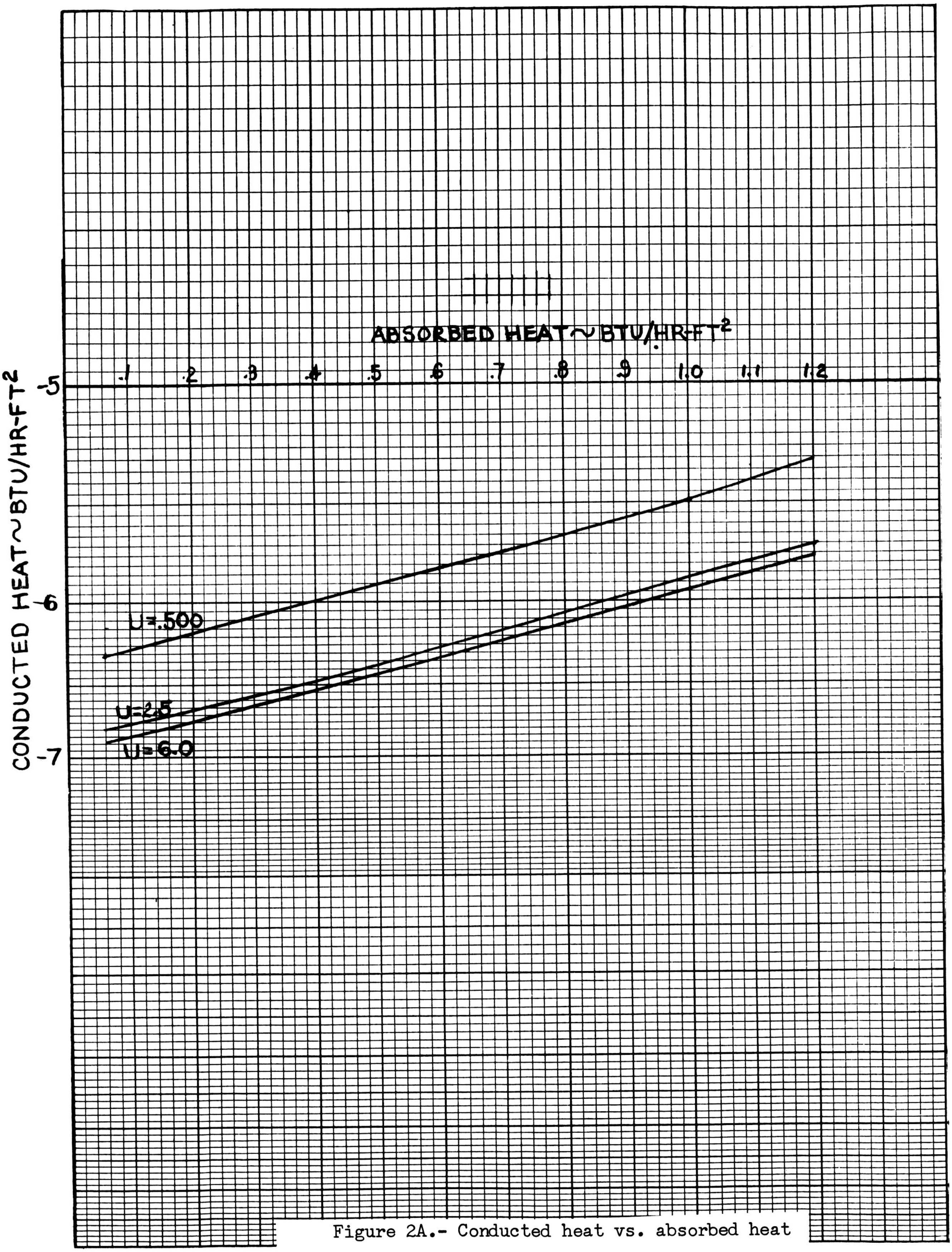


Figure 2A.- Conducted heat vs. absorbed heat

$\epsilon = .05$

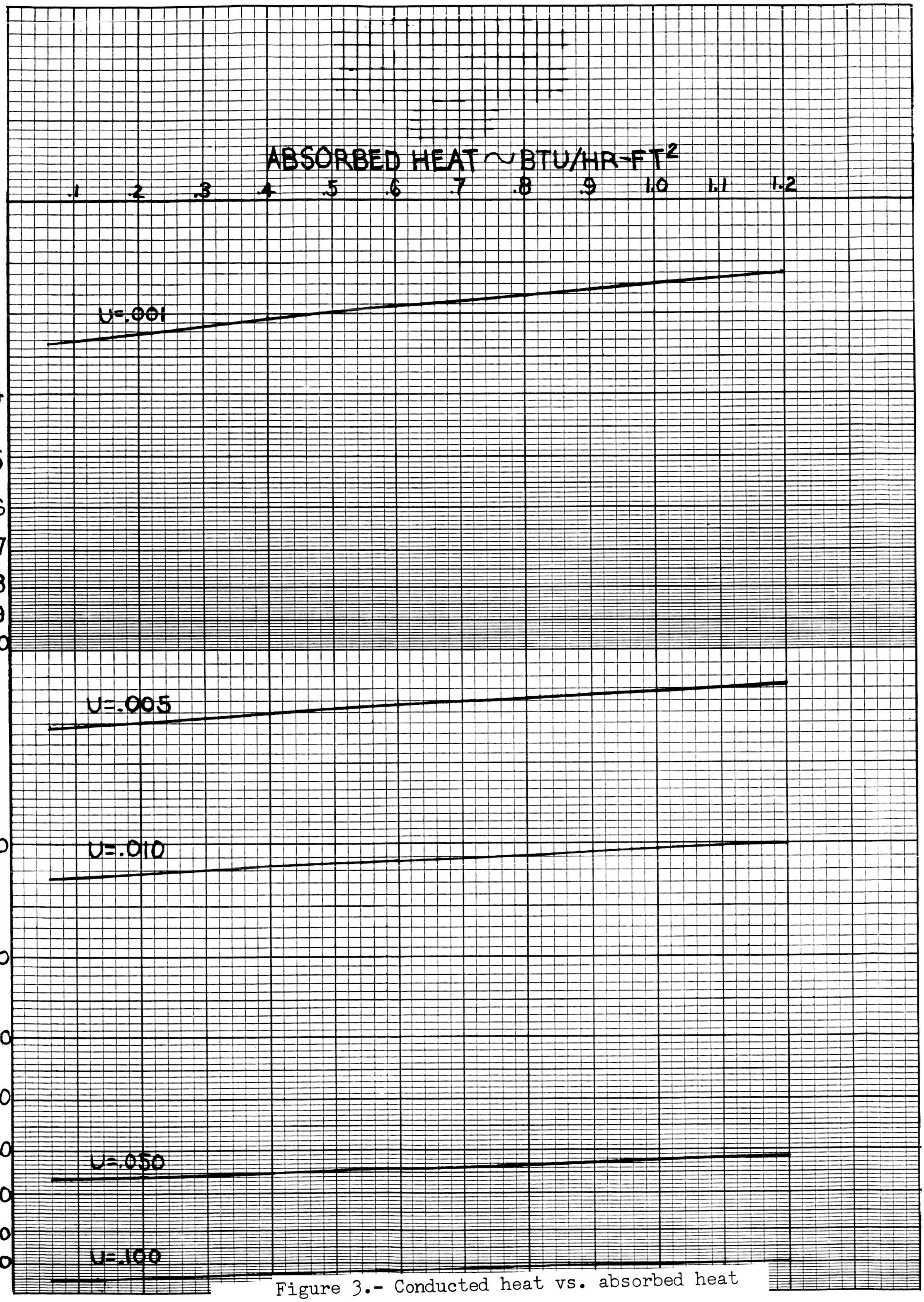


Figure 3.- Conducted heat vs. absorbed heat

$\epsilon = .15$

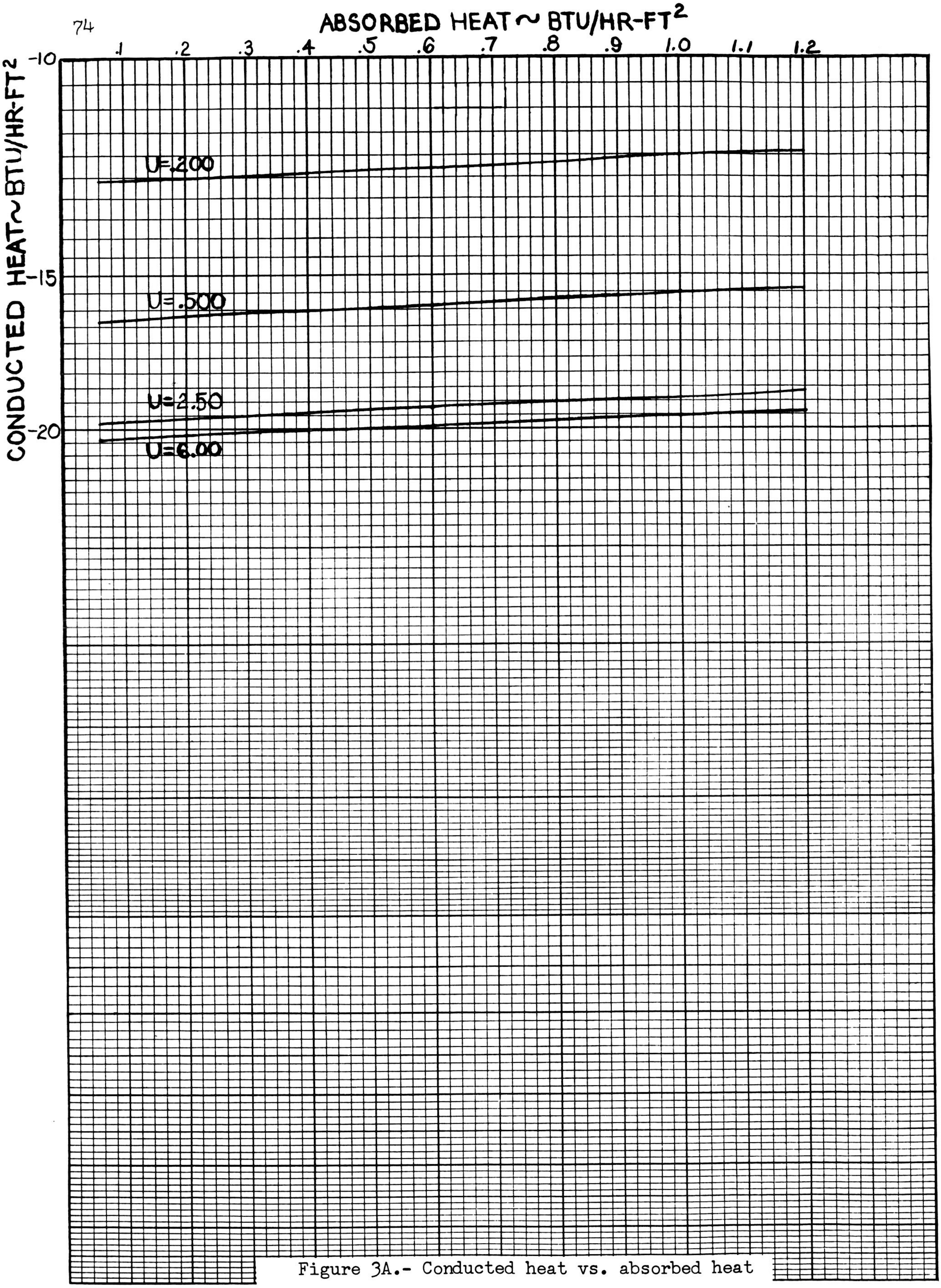


Figure 3A.- Conducted heat vs. absorbed heat

$\epsilon = .15$

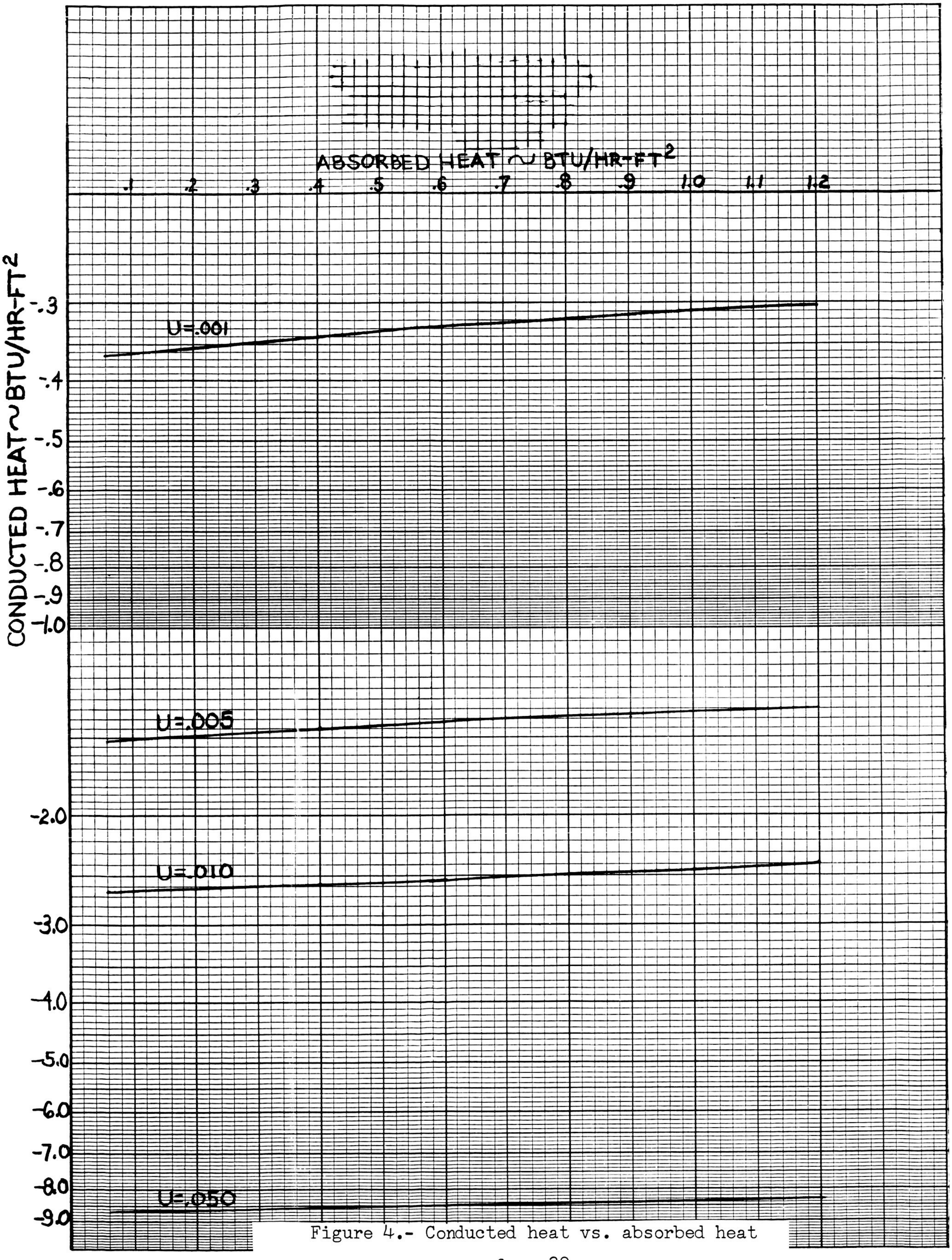


Figure 4.- Conducted heat vs. absorbed heat

$\epsilon = .30$

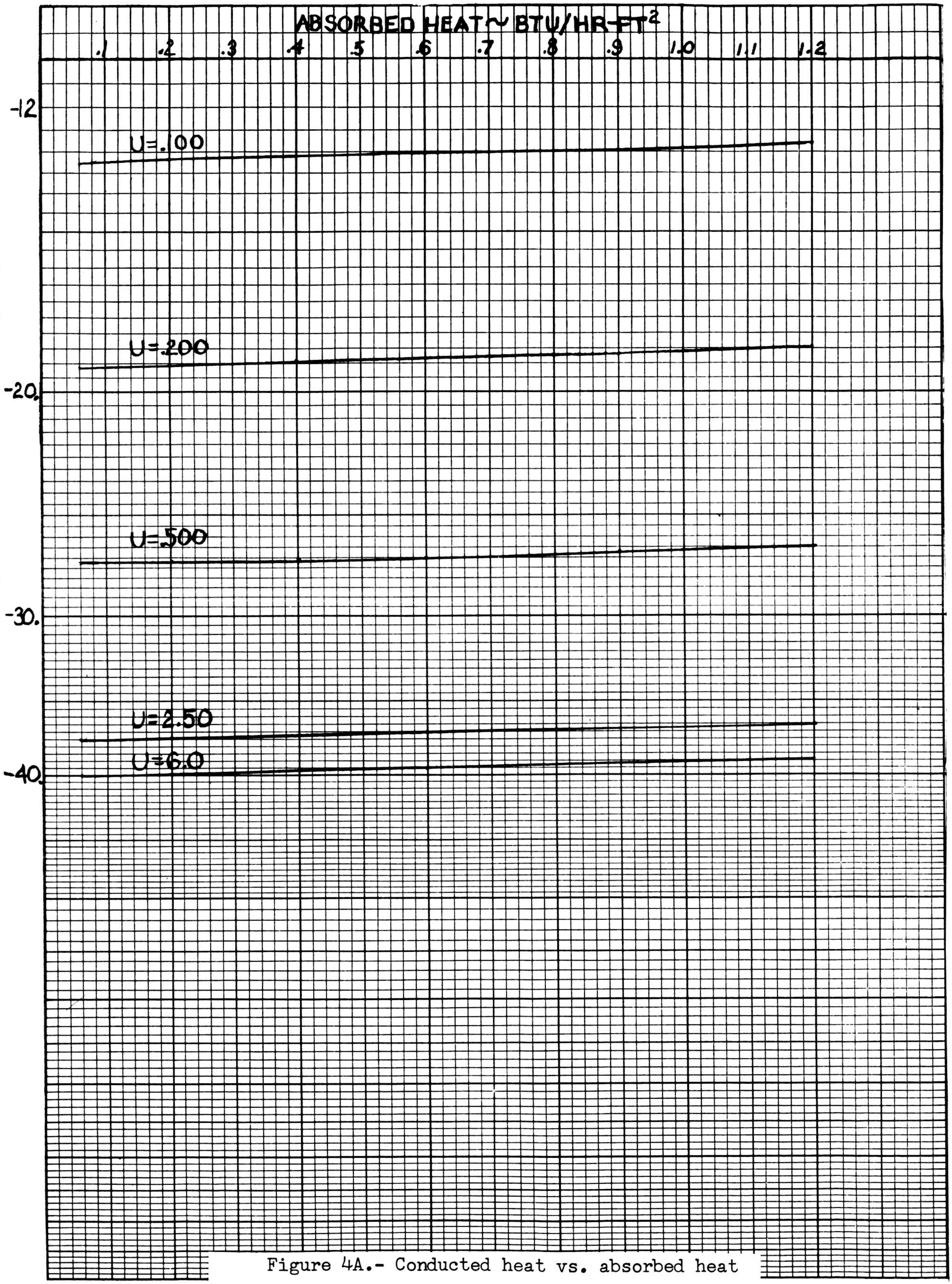


Figure 4A.- Conducted heat vs. absorbed heat

$\epsilon = .30$

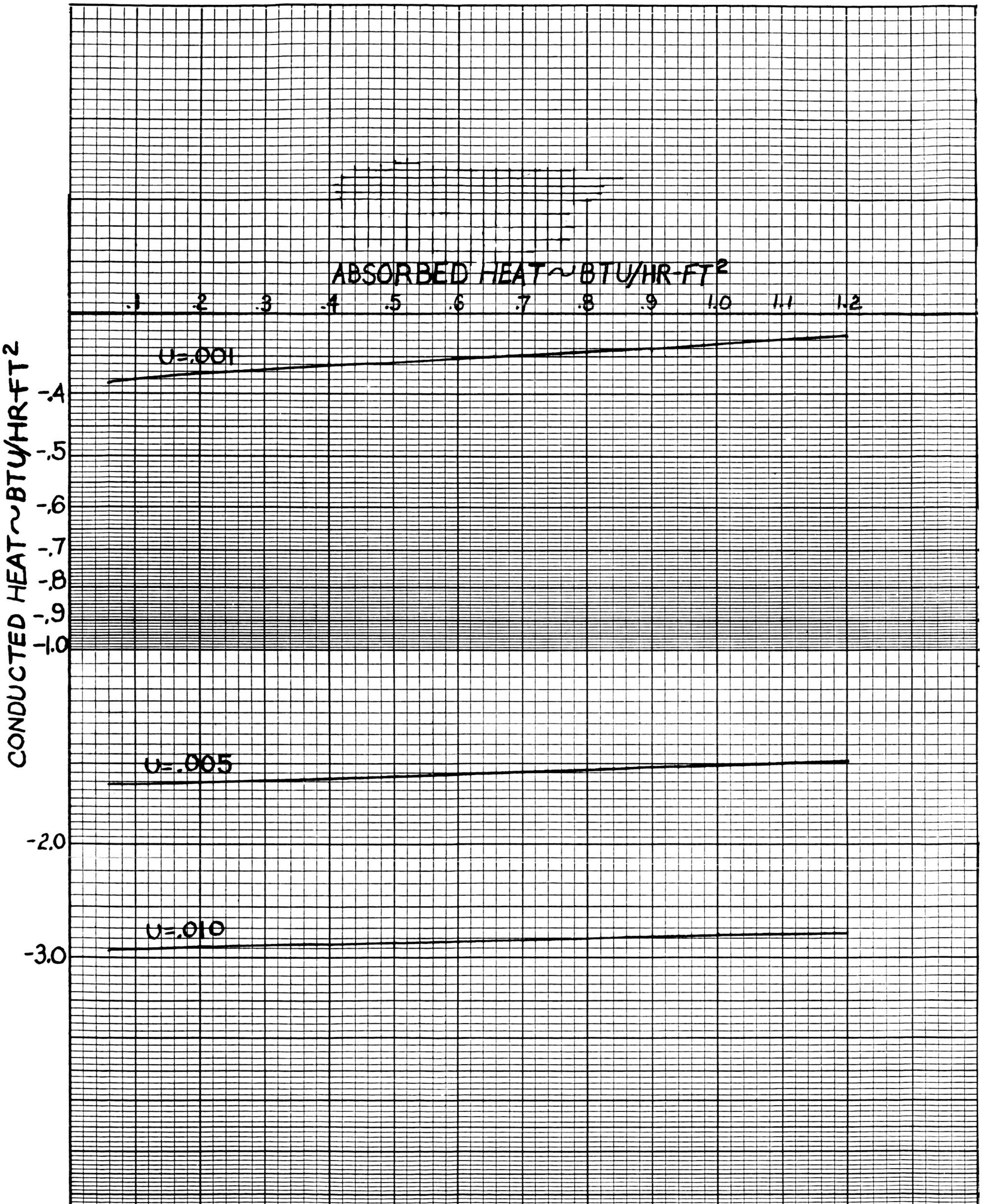


Figure 5.- Conducted heat vs. absorbed heat

$\epsilon = .50$

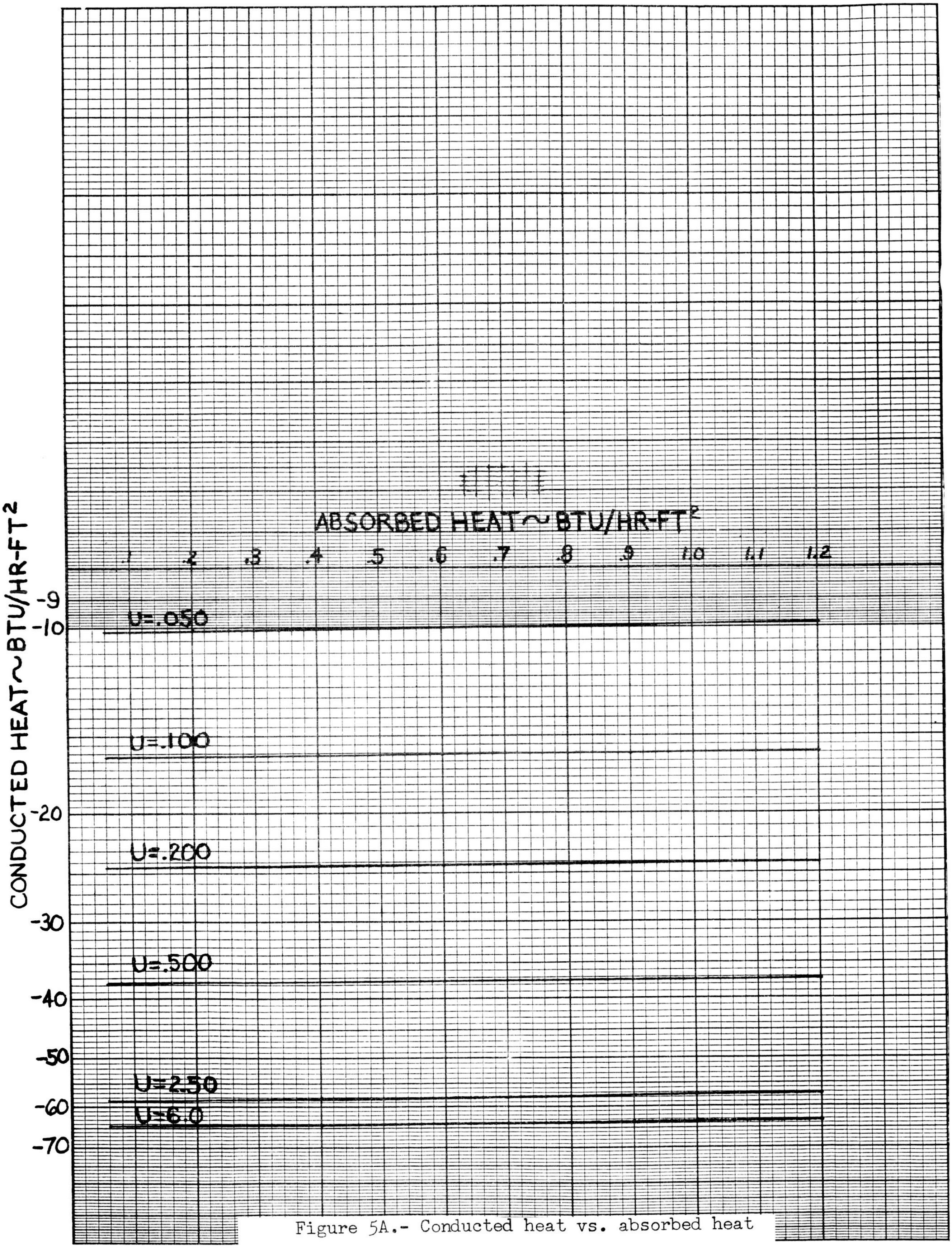


Figure 5A.- Conducted heat vs. absorbed heat

ϵ = .50

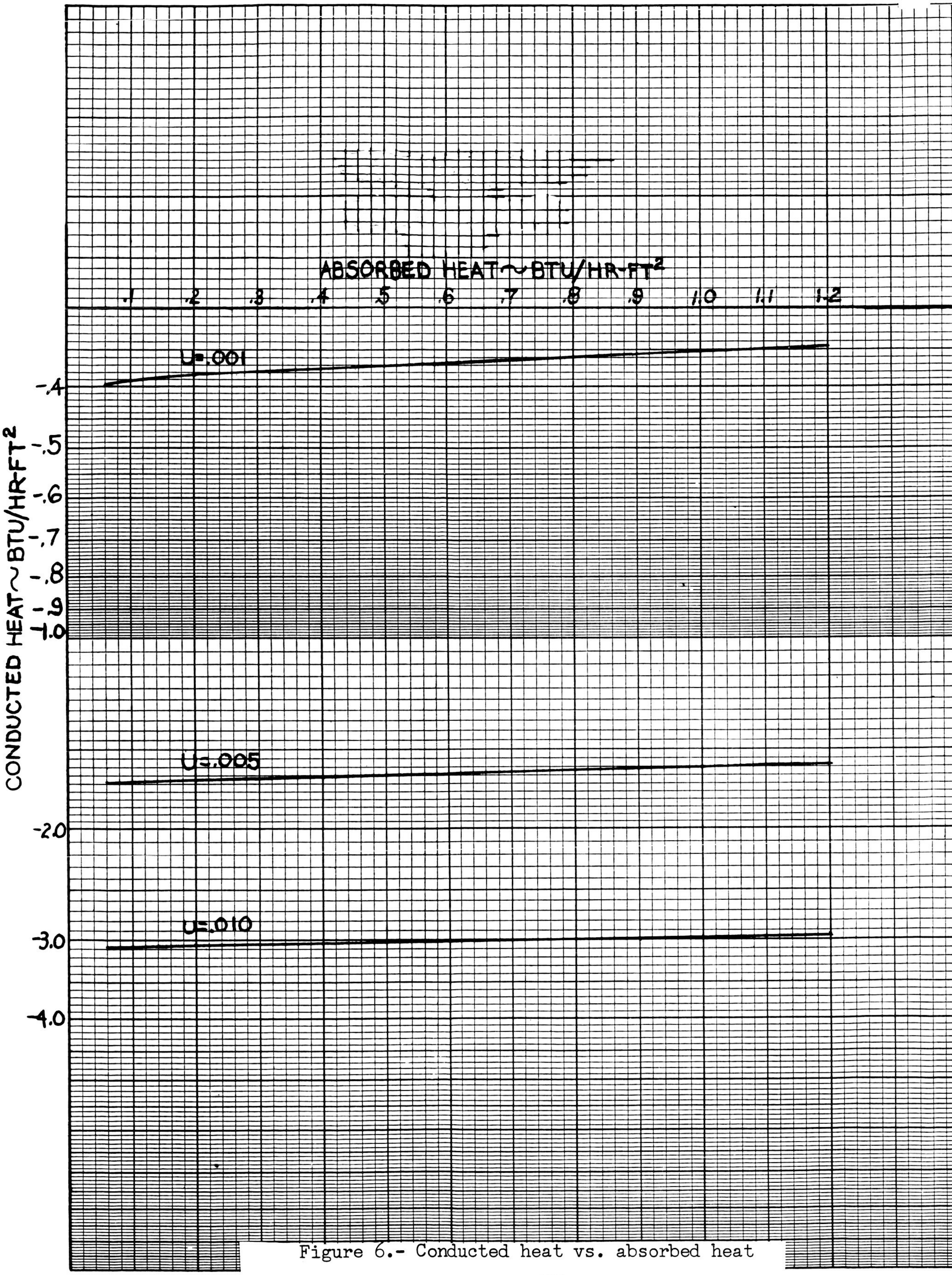


Figure 6.- Conducted heat vs. absorbed heat

$\epsilon = .70$

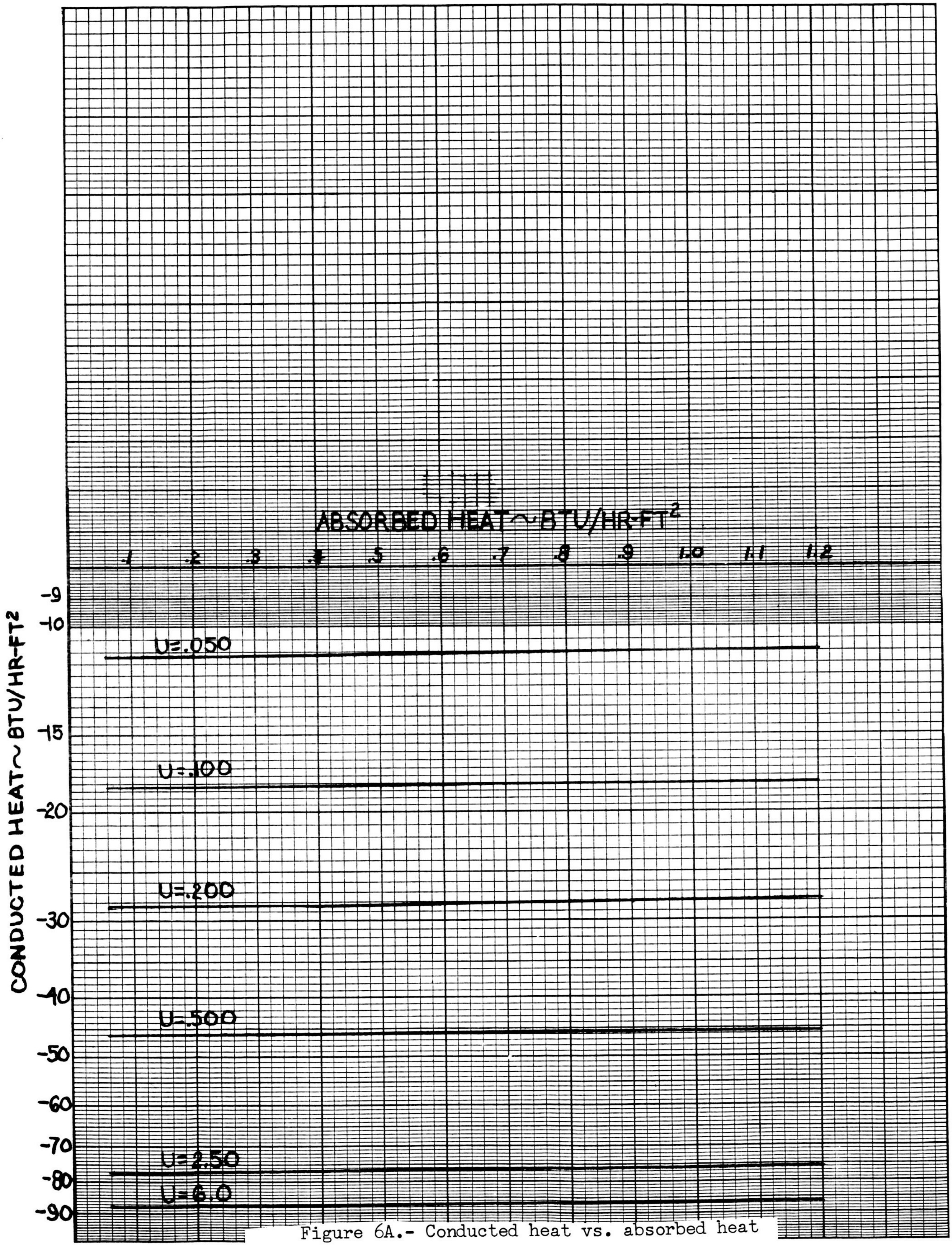


Figure 6A.- Conducted heat vs. absorbed heat

$\epsilon = .70$

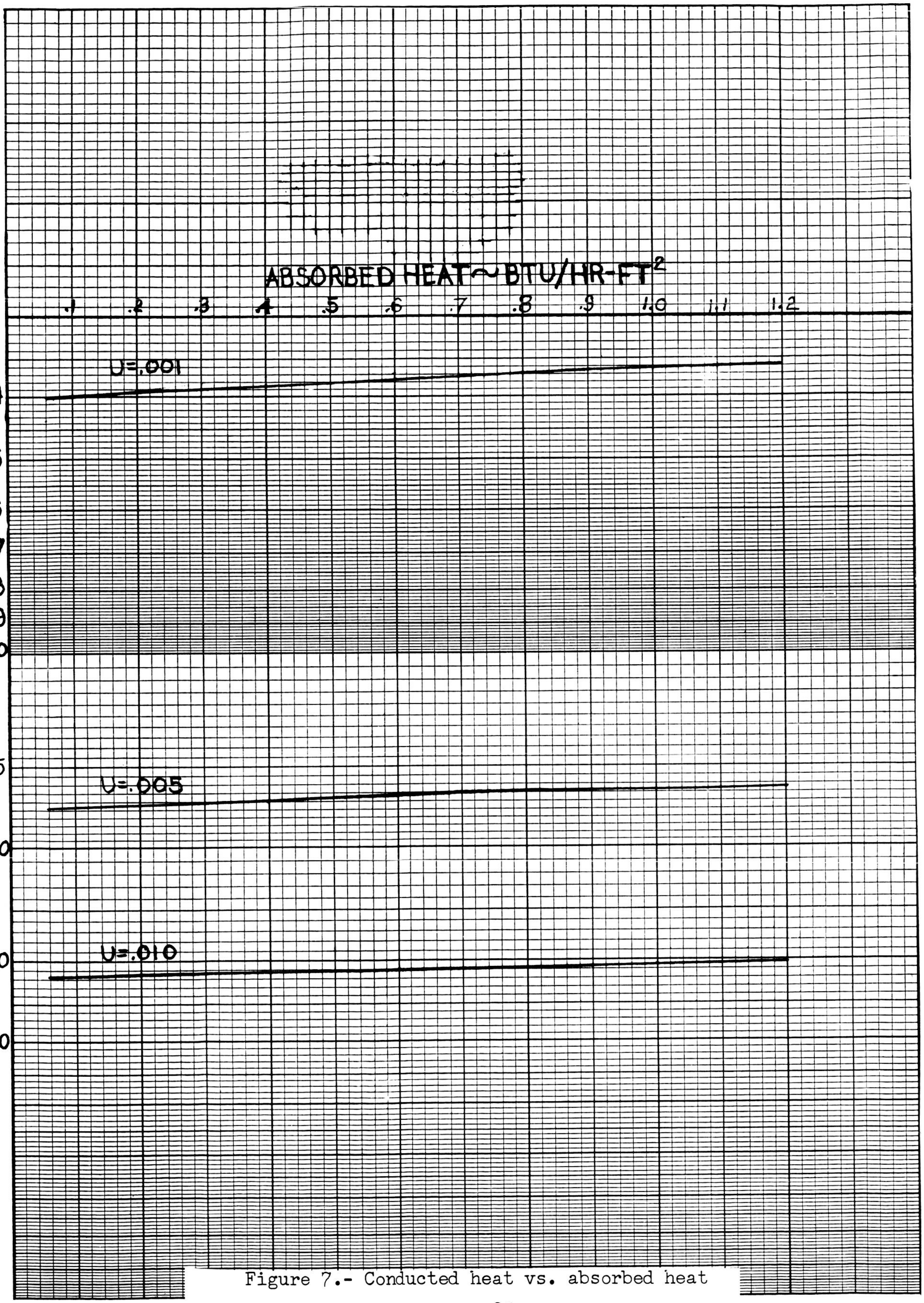


Figure 7.- Conducted heat vs. absorbed heat

ϵ = .85

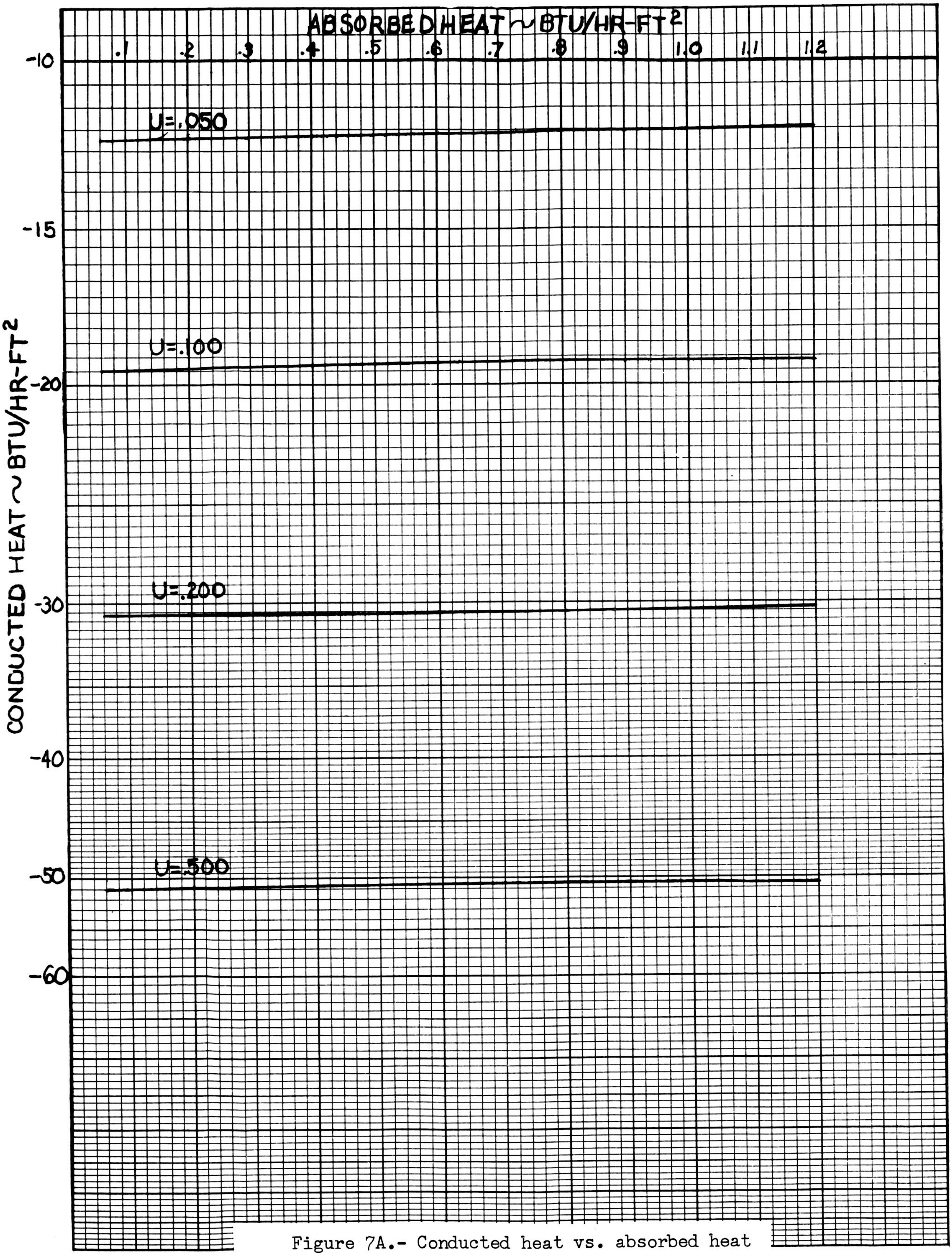


Figure 7A.- Conducted heat vs. absorbed heat

$\epsilon = .85$

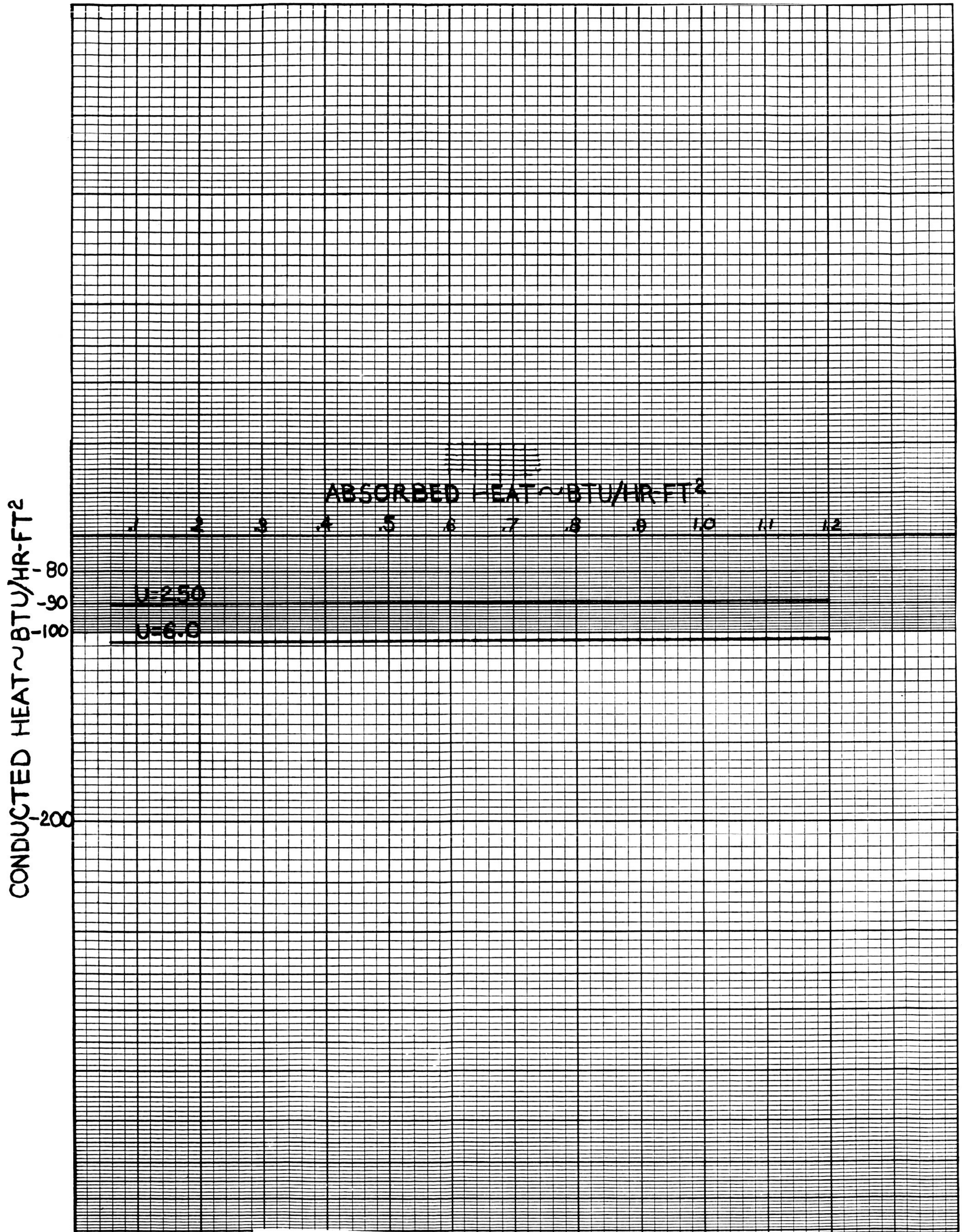


Figure 7B.- Conducted heat vs. absorbed heat

$\epsilon = .85$

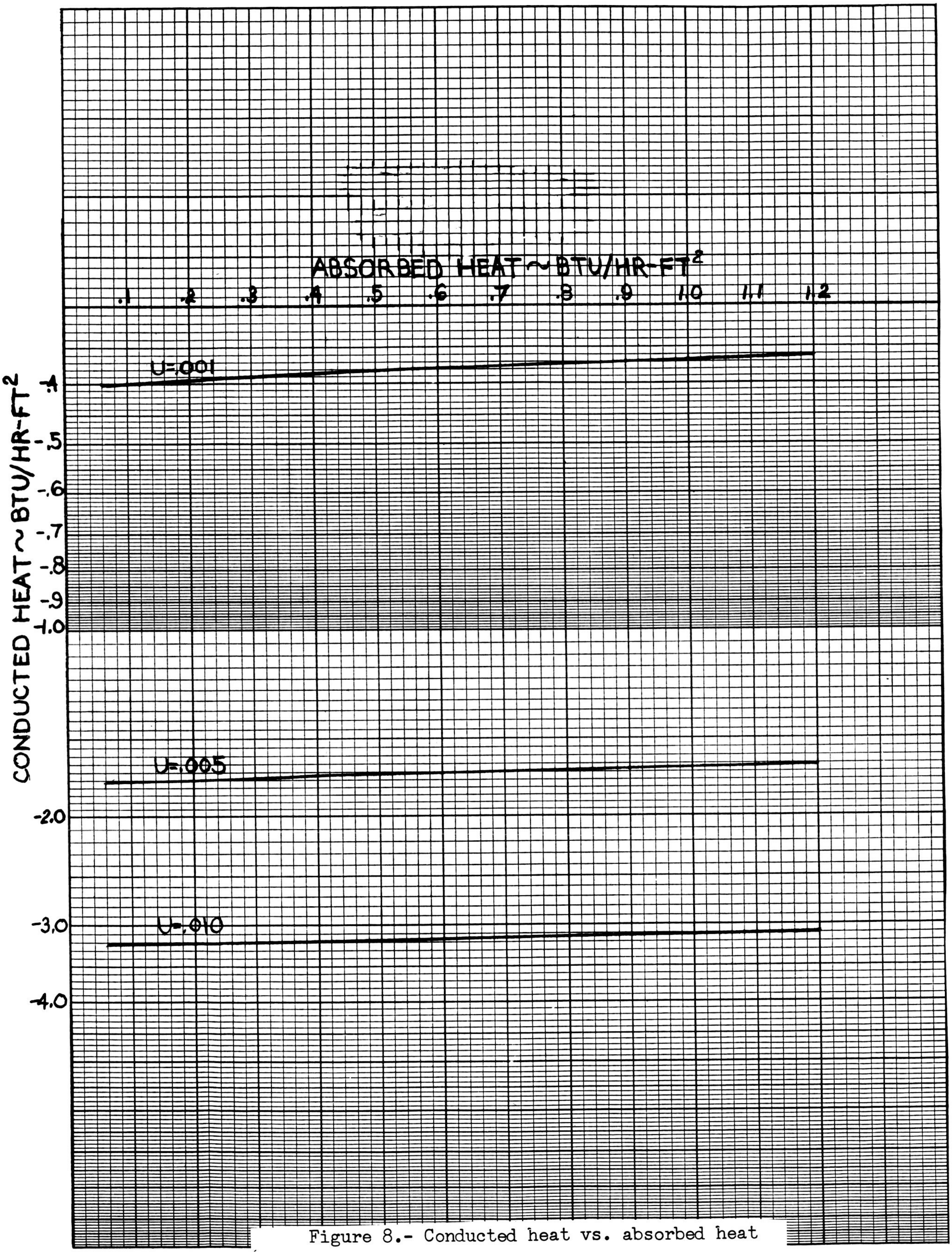


Figure 8.- Conducted heat vs. absorbed heat

$\epsilon = .95$

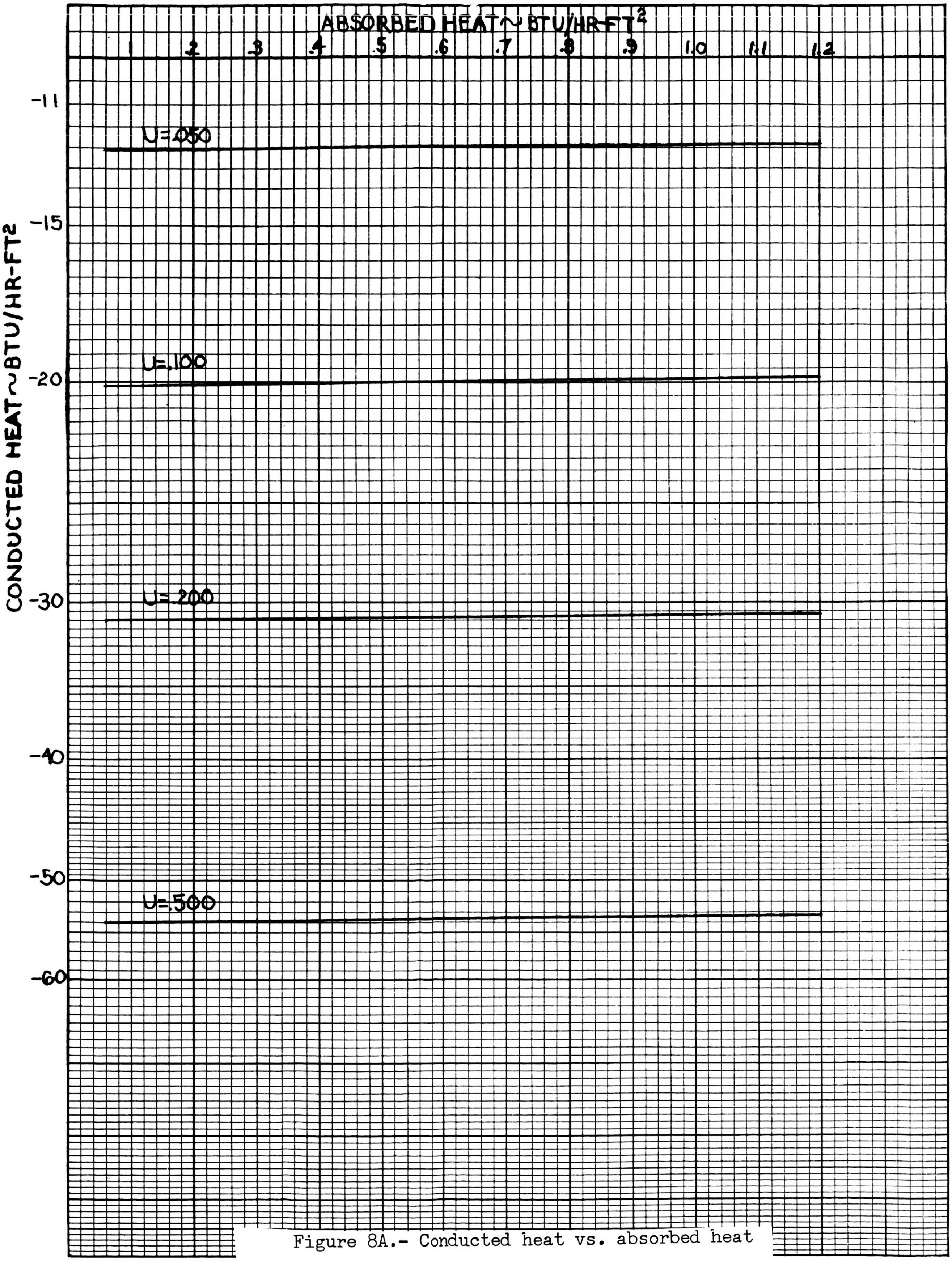


Figure 8A.- Conducted heat vs. absorbed heat

$\epsilon = .95$

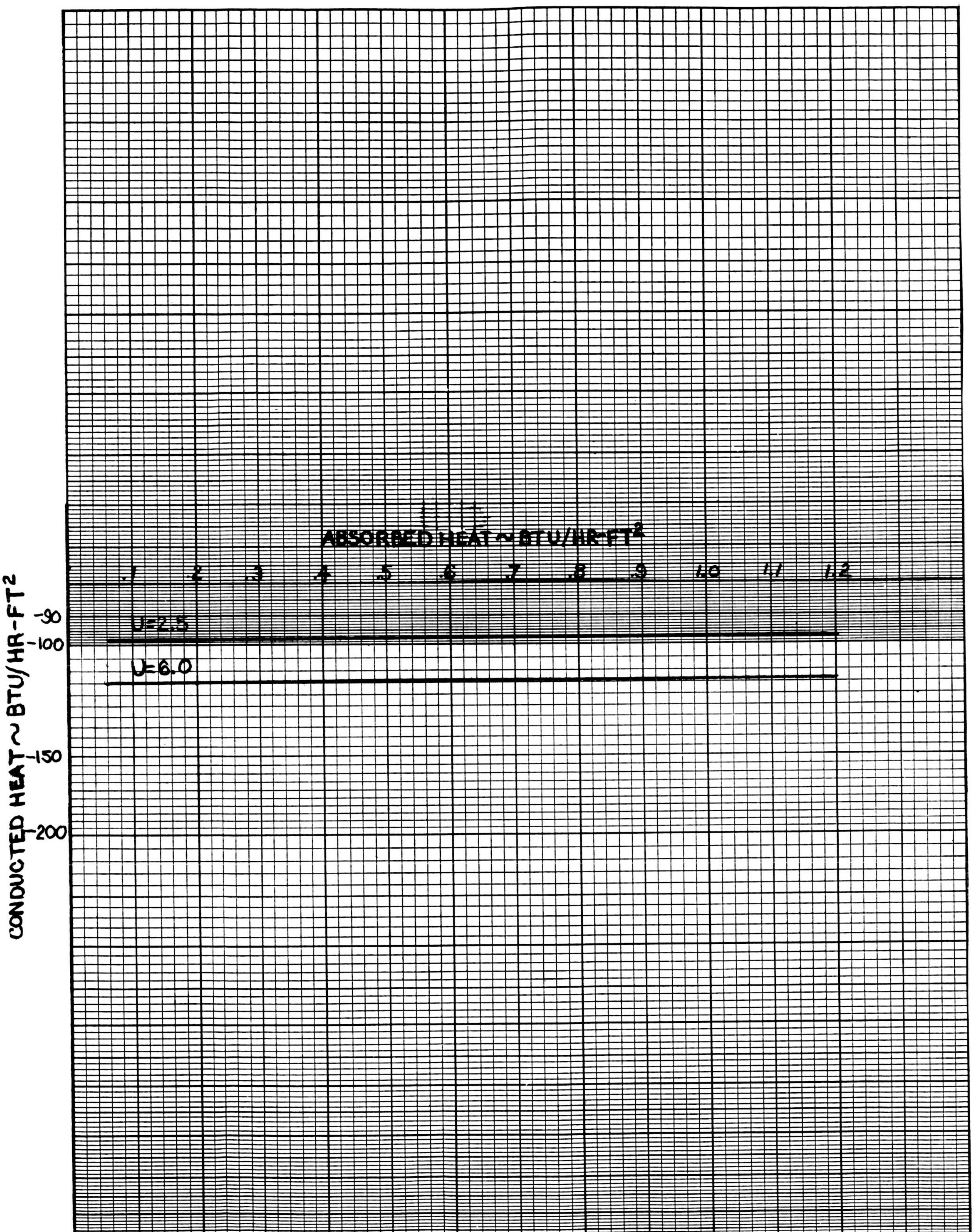


Figure 8B.- Conducted heat vs. absorbed heat

$\epsilon = .95$